Jurnal Kejuruteraan 36(1) 2024: 95-112 https://doi.org/10.17576/jkukm-2024-36(1)-10

An Updated Model Using a Reflection Coefficient for Predicting Performance of Pressure-Retarded Osmosis

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Received 18 March 2023, Received in revised form 22 May 2023 Accepted 22 June 2023, Available online 30 January 2024

ABSTRACT

Mathematical model was used to predict the performance of membrane process. In this study, an updatedmathematical model has been developed to study the forward osmosis (FO) and pressure-retarded osmosis (PRO) processes. This model has been advanced by taking into consideration the reflection coefficient, internal and external concentration polarizations, and structural membrane parameters, as well as the equations of applied pressure and mass transport for feed and draw solutions together. The model was validated through prediction of the water and salt fluxes using the membrane performance data published in other articles. The estimated values of the reflection coefficient ranged from 0.868 to 0.9 for FO and 0.9 to 0.95 for PRO. For this reason, it is not possible to consider the reflection coefficient to be equal to one as normally assumed in membrane modeling study. Other findings have showed that the varying salt fluxes at different concentrations and cross-flow velocities adversely impacted the FO and PRO modules. Internal and external concentration polarizations have been studied and compared with their effect on the effectiveness of the FO/PRO process. The model has demonstrated its ability to predict flux in the PRO greater than FO because of the model primary reliance on the applied pressure to drive the osmotic process. The ratio of J_2/J_w must be effectively managed to correspond with operating limits and the B_2 value must also be kept to a minimum in order to avert the drastical drop in the flux, the fouling, and the membrane damage.

Keywords: Pressure-retarded osmosis; forward osmosis; reflection coefficient; concentration polarization; mathematical model; specific salt flux ratio.

INTRODUCTION

Clean water and renewable energy are vital to support the human civilization for sustainable development. Recently, the depletion in fossil fuel resources, global warming, the geopolitical effects, and the armed disputes every now and then have led to a continuous and significant rise in energy prices (Asif & Muneer 2007; Elimelech & Phillip 2011; Yip et al. 2011). According to World Health Organization expectation, 50% of the humankind will suffer watershortage and most of them will be in developing and poor countries (Tana et al. 2018). These challenges force humankind to develop and increase the production of renewable energy. Osmotic energy, besides its other applications such as desalination, food preservation, and medicine, is considered one of the renewable sources of energy through a process known as pressure retarded osmosis (PRO) (Asif & Muneer 2007; Yip et al. 2011). This form of energy is released when two solutions with a gradient in salinity are mixed in a membrane module at appropriate pressures. The difference in solutions concentration allows the extraction of the chemical potential energy by exploiting the osmotic pressure difference (Elimelech & Phillip 2011; Yip et al. 2011). Due to the difference in osmotic pressure, the diluted solution is passed through from the "feed solution" across membrane module towards the concentrated "draw solution". Expansion in volume at the high-pressure side of the draw solution leads to the production of a hydraulic pressure that can be employed to extract work and then drive a hydro-turbine to generate the electrical energy (Cheng & Chung 2017; Yip et al. 2011). Globally, the chemical potential for this osmotic energy is estimated to be about 1600-2000 TWh/year, which may possibly contribute a considerable part of the global energy needs (Cheng & Chung 2017; Sivertsen et al. 2012).

Mathematical models in PRO are crucial to evaluate and predict the performance of the process under different operating conditions. In order to move this technology closer to practical applications, PRO models have been developed by including the design of systems with practical configurations, influence of the concentration polarization, impact of the specific ratio of reverse salt to water fluxes, and cost estimation into consideration. With a wide variety of membranes such as the spiral wound, hollow fiber and flat sheet membranes have been developed, the mathematical models have to be updated too. Researchers have developed several models related to PRO process (Bui et al. 2015; Soltani & Struchtrup 2019). Loeb thought that the support layer is a boundary layer in which water flux is a function of concentrations and concentration gradients. Loeb adopted the fact that concentration is related to the osmotic

pressure and the transport of water at support layer occurs by diffusion force, and is negligible to salt flux and external concentration polarization (ECP) (Loeb et al. 1976). Lee et al. developed a model that was the first to consider the effect of internal concentration polarization (ICP) in the PRO process by assuming the ratio of salt concentrations is equal to the ratio of osmotic pressures, which neglects the ECP effect (Lee et al. 1981). Achilli et al. evolved the model by Lee et al. by taking into consideration the effect of ECP, which was further developed by McCutcheon and Elimelech (Achilli et al. 2009). Yip et al. have developed the preceding model and included the effect of ECP and reverse salt leakage, assuming relationship between the osmotic pressure and salt concentration is linear, whereas the Achilli model disregarded the lost in the draw solution by its effect on ECP and reverse salt flux (Yip et al. 2011). Bui et al. expanded the Yip model to include the concentrative ECP effect at the feed side and considered the equal mass transfer coefficient for draw and feed solutions $(\mathbf{k}_{\mathbf{F}} = \mathbf{k}_{\mathbf{D}})$, whereas the Yip model neglected these factors. The model by Bui et al. improved the accuracy of the calculations for water and salt fluxes (Touati et al. 2017).

Osmotic power density evaluation must consider both salt and water fluxes, which necessitate determining the fluxes across the membrane by regulating the driving forces $(\Delta \mathbf{p})$ in the active and support sides. However, the specific reverse solute flux (J_s/J_w) could be used to quantify the reversible salt diffusion (RSD) with mass transfer at the active layer of membrane, as well as, this specific ratio (i.e., J_s/J_w) has the influence on the salt flux diffusion on the FO/PRO process as a result of the fact that is close relation between the water and salt fluxes. These specific ratios for the salt and water fluxes (J_g/J_w) could be allowed to have a minor deviation at an ideal semi-permeability with a theoretical variation for the solute flux at the increase in the concentration for the draw solution. Many studies have demonstrated that any increase in the pressure for the PRO will cause an increase in these ratios, and thus, it can be considered that this ratio is a function of the pressure and the temperature for all configurations of PRO systems (Touati et al. 2017; Wu 2019; Wu & Field 2019; Yaroshchuk 2017). Most of the previous studies has assumed the value of σ to be equal to 1.0, however, the real value should be deviated from 1.0 as the membrane is not in ideal state (Bui et al. 2015)(Su & Chung 2011). Additionally, the influence of the solute resistivity value (i.e., reflection coefficient σ) on the flux values for PRO has to be considered in order to modify the micro-math model. Therefore, there was a need for this work to update a micromath model of the FO/PRO system by depending on the J_{s}/J_{w} ratio and taking into consideration the reflection coefficient (σ).

The main objective of this work is to develop a simplified mathematical model to evaluate the FO/PRO process. This model considers the impact of the reflection coefficient, salt flux, and internal and external polarization on the water flux produced through the FO/PRO process. To do so, this work utilize the $J_{\mathfrak{s}}/J_{\mathfrak{w}}$ to compute more accurate water and salt fluxes in FO/PRO processes. Another objective is to asses and verify this math model by using available data from previous experimental works and perform the validation by comparing it with the preceding results.

THEORY AND THEORETICAL MODEL

CONCEPTUAL MATHEMATICAL FORMULAS FOR PRO PROCESS

An updated-mathematical modelling has grown to become an imperative technique to investigate the scale-up implementation of PRO and/or FO processes and how to achieve the commercial viability of the practical value \sim 5W/m². Many articles have been published to assess the performance of the PRO process and estimate the impact of mass transfer on the driving force through the membrane, but these models lacked the overall influences. However, internal concentration polarization (ICP) within the support layer, external concentration polarization (ECP) at the draw solution side close to the membrane surface, and the reverse salt permeation through the membrane will affect the membrane performance.

In this part, the essential concepts of the mathematical models will be given. The osmotic pressure (π) is defined as the minimum pressure of any draw solution to overcome water influx from the feed water. It can be determined using the following Van't Hoff common equation:

$$\pi = i_{\nu} CR_{g} T$$
(1)

The Van't Hoff equation is the most essential equation in the PRO process that is used to evaluate the chemical potentials by utilizing the concentrated solution to generate power. In this equation, t_{ν} is referred to as the Van't Hoff coefficient and representing the degree of dissociation, the osmotic pressure (π), the concentration of solute in the solution (C), which is called the molarity of the solution, the universal gas constant ($\mathbf{R}_{\mathbf{g}}$), and the absolute temperature (T) (Johnson et al. 2018; Van't Hoff 1921; Yasukawa et al. 2015). The water flux term in the perfect membrane and for ideal hydrodynamics can be expressed in terms of the diffusivity of solutes as in the following equation (Ho Chae et al. 2019; Lonsdale et al. 1965): where J_w and D_m are the water flux and water diffusion coefficient in the membrane, respectively, whereas C(x) is the concentration of solute at (x), which represents the distance from the membrane surface. According to Henry's law, the chemical potential can be expressed as $d\mu = -\frac{R_g T d C(x)}{C(x)}$, and Eq (2) becomes (Ho Chae et al. 2019; Lonsdale et al. 1965):

$$J_{W} = \frac{D_{m}C(x)}{R_{g}T} \frac{d\mu_{W}}{dx} \approx \frac{D_{m}C(x)}{R_{g}T} \frac{\Delta\mu_{W}}{\Delta x}$$
(3)

Because $\Delta \mu_w$ represents the change in the water chemical potential across a membrane, and $\Delta \mu_w$ can be taken as expression correspondence with the thermodynamic definition of chemical potential as:

$$\Delta \mu_{\rm w} = \mathbf{R}_{\rm g} \mathbf{T} \ln \Delta \mathbf{a}_{\rm w} + \overline{\mathbf{V}}_{\rm w} \Delta \mathbf{p} \tag{4}$$

where $\mathbf{a}_{\mathbf{w}}$ indicates the water chemical activity, $\overline{\mathbf{V}}_{\mathbf{w}}$ indicates the partial molar volume of water with the assumption that $\overline{\mathbf{V}}_{\mathbf{w}}$ is independent of the pressure, and finally $\Delta \mathbf{p}$ is the hydraulic or applied pressure. Therefore, Equation (4) can be written as:

$$\Delta \mu_{w} = -\overline{V}_{w} \Delta \pi + \overline{V}_{w} \Delta p = \overline{V}_{w} (\Delta p - \Delta \pi) \quad (5)$$

As a result, the conversion of $(R_g T \ln \Delta a_w)$ into $(-\overline{V}_w \Delta \pi)$ relies on an alternative thermodynamic definition of π as: $\pi = -\frac{R_g T}{\overline{V}_w} \ln \Delta a_w$ (Ho Chae et al. 2019; Madsen et al. 2017). Hence, Equation (3) can be combined with Equation (5) to derive the ultimate relationship of the water flux (J_w) as:

$$J_{w} = \frac{D_{m}C(x)\overline{V}_{w}}{R_{g}T(\Delta x)} (\Delta p - \Delta \pi)$$
(6)

In retarded osmosis, the osmotic pressure (π_i) is higher than the applied hydraulic pressure of the system (Δp) , which leads to the switch between hydraulic pressure and osmotic pressure. On the other side, the set of limitations $(\frac{D_m C(x) \overline{V}_W}{R_g T(\Delta x)})$ on the right-hand side of Equation (6) can interchange with A_W . Lastly, the water flux of the pressure retarded osmosis process may be calculated by:

$$J_w = A_w (\Delta \pi_{act.} - \Delta p) = A_w (\pi_{D, m} - \pi_i - \Delta p) \quad (7)$$

Equation (7) is the common equation used fundamentally to calculate water flux in FO and PRO processes. In equation (7), A_w is the water permeability coefficient, $\pi_{D,m}$ is the osmotic pressure for the draw solution at the surface of the membrane, π_i is the osmotic pressure for the feed solution at the interface of the activesupport layer, which is equal to C_{icp} , and Δp is the difference in the applied hydraulic pressure between the draw and feed sides of the membrane, which is usually equal to zero in FO applications.

PRACTICAL MEMBRANE CONDITION INCLUDING REVERSE SALT FLUX AND CONCENTRATION POLARIZATION

The actual semipermeable membranes are not ideal, and so amount of salt will penetrate across an asymmetric membrane in FO/PRO process. In any asymmetric membrane structure included a thin dense (active) layer located at the top of a porous (support) layer; or salt leakage in the membrane; or a non-ideal flow in the draw solution stream channels, concentration polarization phenomena (CP), all these will appear in the PRO process, as shown in Figure 1 (Ge et al. 2013).



FIGURE 1. Illustration of the concentration profile across the semi- permeable asymmetric membrane of the FO/PRO process

The effect of salt penetration on the membrane performance can be observed by reducing the effective osmotic pressure difference throughout the PRO membrane (Lee et al. 1981; Straub et al. 2016; Tran et al. 2016). In order to recognize CP, the main transport phenomena in the nearby PRO membrane should be known. CP is a major phenomenon that inevitably could emerge in any FO/PRO process. It normally weakens the activity of the osmotic pressure difference at the membrane sides, resulting in the accumulation or depletion of solutes near an interface. Due to water flow through the membrane, solutes will be concentrated in the feed side at the surface of the membrane and diluted in the other side of the membrane. Because of the membrane structure is asymmetric, it leads to the formation of ECP at the active layer surface and ICP at the support layer (Lee et al. 1981; McCutcheon & Elimelech 2006; Zhang et al. 2016).

INTERNAL CONCENTRATION POLARIZATION

Internal concentration polarization (ICP) can be described as the accumulated solvents that continuously increase in the support layer interfaced with the PRO membrane. It is facing the feed side of the membrane that leads to a reduction of the transmembrane driving-force with the appearance of a stagnant boundary layer and increasing osmotic pressure of the feed solution. ICP is stimulated from the porous substrate (support layer), which will encourage the growth in the sub-layer concentration at the active-support interface from ${\boldsymbol{\mathsf{C}}}_{{\boldsymbol{\mathsf{F}}},m}$ to ${\boldsymbol{\mathsf{C}}}_i$, as shown in Fig. 1. This effect detrimentally increases π_i (osmotic pressure for the feed solution at the interface of the active-support layer), which occurs by the increase in the solute concentration at the feed membrane interface. Consequently, it will lead to a reduction of the trans-membrane driving force and a dramatic decrease in the water flux (Lee et al. 1981; Su & Chung 2011; Touati & Tadeo 2017).

In the PRO systems, the water flux moves from the feed direction into the draw direction, while the salt flux runs from the draw direction into the feed direction. The reverse directions of each flux result from the dissimilarities in the structure for the membrane layers, which lead to the isolation of the salts inside a membrane. In spite of the salts attempting to flow into the feed side, it is unsuccessful as a result of the water flux serving to drive the salt in the direction of the draw side. Subsequently, quantities of salts are trapped constantly at the PRO membrane to form another concentration that is situated inside the membrane porous layer and then it could represent as ICP (Achilli et al. 2010; Klaysom et al. 2013; Zhang et al. 2016). Another burden induced on the PRO process that is effectively lead to aggravate the performance to this process. As a result, to interact among the combinations of solutes or microbes, the microorganisms in the feed and draw solutions will form byproducts, for example, polysaccharides and proteins, and then accumulate within a membrane and produces a serious (ICP). Furthermore, an increase in microorganisms will cause clogging in the pores of the membrane; thus, the proficiency of the PRO process basically in decline (Ho Chae et al. 2019; Honda et al. 2015). Since the trends for water and salt fluxes in FO/ PRO process is commonly moving in the opposite direction, and ICP is an unavoidable occurrence in the FO/ PRO processes (Wan Nur Syuhada Wan Ata 2019). Therefore, the salt reverse flux will be obviously appearing and then affects the entire process. Reverse salt diffusion will occur due to the gradient in the concentration of solutes between the solution in the draw side and feed side across the semi-permeable membrane. According to Fick's Law, the diffusion of solutes (J_e) can be expressed as:

$$-J_{s} = B_{s} \Delta C = B_{s} (C_{D,m} - C_{F,m})$$
(8)

By referring to Eq (8), the negative sign of the salt flux denotes the direction of salt flow that is opposite the water flow direction, where B_s represents the salt permeability coefficient and $C_{D,m}$, $C_{F,m}$ are the solute concentrations at the active and porous (support) layers at the membrane sides, respectively (Klaysom et al. 2013; Lee et al. 1981; Touati et al. 2016). Due to the water permeation from the feed to the draw (such as osmotic water flux, J_w), the dilution of the draw solution at the support (porous) and draw solution within the boundary layer is caused by the dilutive of the ICP and ECP at the support layer. At the same time, solutes will be diffused from the draw bulk solution by crossing through the porous support towards the interface support with the active layer as a result of the gradient in the concentration from the draw solution dilution. This transport is commonly defined by using the convective diffusion equation to contain a diffusivity term as a cause of the gradient in the solute concentration and a negative convective term as a cause of the water mass flow across the membrane within opposite directions. Due to abovementioned, the sum total of the salt displacement by convection and differences in the salt concentration by diffusion, the mass transfer of salt in the pours (support) layer with boundary layers can be identified as:

$$-J_{s} = D_{sl} \frac{dC(x)}{dx} - J_{w} . C(x)$$
(9)

where C(X) represents the solute concentration at position x and $D_{s,l}$ is the coefficient of diffusion at the support (pours) layer of the membrane, which can be expressed:

$$\mathbf{D}_{\mathrm{gl}} = \frac{\varepsilon \cdot \mathbf{D}}{\tau} \tag{10}$$

By substituting Eq. (10) instead of $D_{s,l}$, Eq (9) for the salt transfer balance can be rewritten as:

$$-J_{g} = \frac{\varepsilon . D}{\tau} \frac{dC(x)}{dx} - J_{w} . C(x)$$
(11)

where $C(\mathbf{X})$ is the solute concentration at position x, D is the salt diffusion coefficient, which is usually denoted as the diffusivity in the bulk solution, ε is the substrate porosity, and τ is the tortuosity of the support layer. Eq (11) can be rearranged as:

$$\frac{dC(x)}{C(x) + \frac{J_x}{J_w}} = \frac{\tau}{\varepsilon.D} \cdot J_w \cdot dx$$
(12)

According to the boundary conditions of Eq. (12) at the porous (support) layer, $C(x)=C_{F,m}$ at (x=0) and $C(x)=C_{icp}$ at (x=t_s). With integration of Eq. (12), the math model to estimate C_{icp} can be expressed as:

$$C_{icp} = (C_{F,m} + \frac{J_s}{J_w}) \cdot e^{J_w \cdot K} - \frac{J_s}{J_w}$$
 (13)

where \mathbf{K} represents the solute of the resistivity to salt transport in the porous (support) layer, and it can be described as:

$$K = \frac{\tau \cdot t_s}{\varepsilon \cdot D} = \frac{s}{D}$$
(14)

where S can be described as $\frac{\tau_{i}t_{s}}{\epsilon}$, and that defined as a structural parameter. It can be categorized into three membrane parameters; water permeability coefficient (A_w) , salt permeability coefficient (B,), and structure parameter (S), which can be considered the major parameters for the membrane properties (Achilli et al. 2009; Attarde et al. 2016; Bui et al. 2015; Ho Chae et al. 2019; McCutcheon & Elimelech 2006). Eq. (13) can be considered as accurate equation and can be used to evaluate the internal concentration polarization in the PRO systems with any type of membrane fabricated in the PRO process. The improvement in A_w value in Eq. (7) could lead to increases in the water flux in the PRO process and mostly have to occur the augmented performing of this process. Meanwhile, the salt flux must reduce as so as possibility by repressing value of B_s in accordance to Eq. (8). In accordance to the above-mentioned, K emergence in Eq. (14) is proportional to the S value, and C_{icp} will augment when K augments. Therefore, the value of S must remain as a minimum value to keep on the high value for the difference of the osmotic pressure. However, the decrease in the S value should be balanced with the tortuosity and the thickness of the porous (support) layer for the reason that any excessive values for those terms could have a detrimental influence on the strength of membrane

structure. Because the S term is equal to $(\frac{\tau t_s}{\epsilon})$, the support layer thickness with the tortuosity must be as minimum as the possibility while keeping the porosity as high as possible. In other words, satisfying these features must be considered priority at the fabrication of the FO/PRO membrane.

EXTERNAL CONCENTRATION POLARIZATION

External concentration polarization (ECP) appears in the real FO/PRO process, and two forms of ECPs could be produced as well as it can be considered ECPs as a function of the flow configuration and operation conditions. In relation to localities where ECPs occur, dilutive ECP occurs at a boundary locality in between the bulk draw solution and the active layer of the membrane. The dilutive ECP occurs at the draw side membrane in the PRO process because the solutes are diluted at the boundary locality in the surface of the active layer. It becomes diluted due to cross water from the feed side through a membrane and result in that the difference in effective osmotic pressure would diminish ($\pi_{D,b}$ to $\pi_{D,m}$) with expression dilutive

ECP modulus as: $\left(\frac{\pi_{D,m}}{\pi_{D,b}}\right) = e^{-\frac{l_W}{k}}$, and also $\delta = \frac{D}{\kappa}$ where δ is a thickness of the boundary layer (Bui et al. 2015; McCutcheon & Elimelech 2006).

The math model can help to estimate the $C_{D,m}$ by applying Eq. (12) and respective boundary conditions: (x)= $C_{D,m}$ at(x=0),and C(x)= $C_{D,b}$ at(x= δ_D) and can be integrated as:

$$C_{D,m} = (C_{D,b} + \frac{J_s}{J_w}) \cdot e^{-\frac{J_w}{k_D}} - \frac{J_s}{J_w}$$
 (15)

Meanwhile, another type of ECP will occur at the boundary locality in between the bulk feed solution and the surface support layer of the membrane; this is called the concentrative ECP. As a result, in order to flow water, the solutes will be transported from the bulk solution towards the active layer surface to allow water permeation into this layer and leave behind a solute in higher concentrations. Therefore, the feed solutes would be accumulated at a boundary locality of the active layer surface, which causes the increase in the feed concentration, and then the difference in the effective osmotic pressure would diminish ($\pi_{F,b}$ to $\pi_{F,m}$), with the expression concentrative ECP modulus as: $(\frac{\pi_{F,m}}{\pi_{F,h}})=e^{\frac{1}{h}}$. McCutcheon et al. proved that $\pi_{F,m}$ is correlated with $\pi_{F,b}$ by what is termed the concentrative ECP modulus. However, it can be assumed that the ratio of the concentration at the

membrane surface for feed solutes to the bulk concentration is equal to the symmetrical ratio of the osmotic pressures. Many researchers have adopted this ECP modulus (Bui et al. 2015; McCutcheon & Elimelech 2006). By Appling the same method, we have integrated Eq. (12) within the boundary conditions:

 $C(x) = C_{F,m}$ at (x=0), and $C(x) = C_{F,b}$ at (x= δ_F) to estimate $C_{F,m}C_{F,m}$ and yield the following math model expression:

$$C_{F,m} = (C_{F,b} + \frac{J_s}{J_w}) \cdot e^{-\frac{J_w}{k_F}} - \frac{J_s}{J_w}$$
(16)

Depending on the Van't Hoff equation with respect to the validation of Eq. (1), $\Delta C_{act.}$ can be determined by subtracting Eq. (15) in to (13) and replacing the $C_{F,m}$ term in Eq. (13) by Eq. (16):

$$\Delta C_{act} = (C_{D, b} + \frac{J_s}{J_w}) \cdot e^{-\frac{J_w}{k_D}} - ([(C_{F, b} + \frac{J_s}{J_w}) \cdot e^{\frac{J_w}{k_F}}] \cdot e^{-J_w \cdot K})$$
(17)

SALT FLUX RATIO (J./J.,)

The salt flux is proportional to water flux in the FO/PRO process, and is described as J_g/J_w , and is called the specific ratio of the salt flux to water flux, which is influenced by the intrinsic transport properties of the membranes. Due to no perfect membranes as selective, a reverse salt flux occurs, leads to leaking of salts. The specific salt ratio is utilized to explain the 'leakiness' of salts (J_g) and moved to opposite direction of water flux (J_w). Based on the theory of diffusion in the solutions for water and solute via active layer, the specific salt ratios can be used in Eq. (10) and Eq. (7) with rearrangement as presented in the flowing relations:

$$\Delta C = \frac{J_s}{B_s}$$
(8a)

$$\Delta \pi = \frac{J_w}{A_w} + \Delta p \tag{7a}$$

By combining Eq. (8a) and Eq. (7a) and using Van't Hoff equation to be solved as follows:

$$\frac{J_{s}}{J_{w}} = \frac{B_{s}}{A_{w}i_{v}R_{g}T} \left(1 + \frac{A_{w}\Delta p}{J_{w}}\right)$$
(18)

The 'leakiness' of salts in the membrane has been adopted by Lee et al. to test the performance of the FO/ PRO process for non-ideal membranes and to evaluate the water flux with the polarization impact on the process. Also, Yaroshchuk has suggested that 'leakiness' and the 'osmosis breakthrough' mode under some conditions with the membrane might occur even to the extent that with the appropriate membranes, reverse solute diffusion would be eliminated (She et al. 2012; Wu 2019; Yaroshchuk 2017). According to the Van't Hoff theory with validated it in concentration regions, the solute concentration is linearly proportional to the osmotic pressure, which can be considered that:

$$\pi_{\mathbf{D},\mathbf{m}} = i_{\nu} \cdot \mathbf{R}_{\mathbf{g}} \cdot \mathbf{T} \cdot \mathbf{C}_{\mathbf{D},\mathbf{m}}$$
(19a)

$$\pi_{icp} = i_{\nu} R_g T.C_{icp}$$
 (19b)

$$\pi_{\mathbf{F},\mathbf{m}} = i_{\nu} \cdot \mathbf{R}_{\mathbf{g}} \cdot \mathbf{T} \cdot \mathbf{C}_{\mathbf{F},\mathbf{m}}$$
(19c)

As mentioned in Eq. (13), (15), and (16), the C_{icp} , $C_{D,m}$, and $C_{F,m}$ specified the influences of the internal and external concentration polarization on the feed and draw solution sides. According to substitute the specific ratio of salt flux (J_s/J_w) by with Eq. (18) in Eq. (17) and respect the validation of Eq. (19a), (19b), and (19c) besides taking into consideration the reflection coefficient ($\sigma\sigma$), a new math-micro model to determine the water flux can be written as:

$$J_{w}^{FO} = A_{w} \left(\sigma \left[\left\{ \pi_{D,b} + \frac{B_{s}}{A_{w}} \left(1 + \frac{A_{w}\Delta p}{J_{w}} \right) \right\}, e^{-\frac{J_{w}}{k_{D}}} - \left\{ \pi_{F,b} + \frac{B_{s}}{A_{w}} \left(1 + \frac{A_{w}\Delta p}{J_{w}} \right) \right\}, e^{J_{w}K}, e^{\frac{J_{w}}{k_{P}}} \right] \right)$$

$$J_{w}^{PRO} = A_{w} \left(\sigma \left[\left\{ \pi_{D,b} + \frac{B_{s}}{A_{w}} \left(1 + \frac{A_{w}\Delta p}{J_{w}} \right) \right\}, e^{-\frac{J_{w}}{k_{D}}} - \left\{ \pi_{F,b} + \frac{B_{s}}{A_{w}} \left(1 + \frac{A_{w}\Delta p}{J_{w}} \right) \right\}, e^{J_{w}K}, e^{\frac{J_{w}}{k_{P}}} - \Delta p \right)$$

$$(20)$$

As a consequence of the rearrangement and combination with the Van't Hoff equation Eq. (1) and Eq. (7a), the reverse salt flux can be expressed as:

$$J_{s} = \frac{B_{s}}{A_{w}i_{v}R_{g}T} J_{w} \left(1 + \frac{A_{w}\Delta p}{J_{w}}\right)$$
(22)

REFLECTION COEFFICIENT IMPORTANCE

The reflection coefficient is a function of the solute and membrane characteristics, which rely on the membrane features (membrane selection, structure of parameters) and solution properties (diffusivity, hydrodynamic forms), and the range values of the reflection coefficient are between zero at the solute and solvent pass through membrane at the same concentration ratio close to the bulk solution and unity when all solutes are rejected (Anderson & Malone 1974; Pusch & Riley 1974; Su & Chung 2011). Therefore, determination of the reflection coefficient could be predicted to produce the best models for osmotic fluxes and designs of FO/PRO membranes, and the reflection coefficient can be calculated by using the following equation (Bui et al. 2015; Johnson et al. 2018):

$$\sigma = \frac{\frac{1}{B_{s}}}{\frac{1}{B_{s} + \frac{1}{k_{p}} + \frac{1}{k_{D}} + K}}$$
(23)

The denominator represents a summation of the solute resistivity that is caused by the membrane selective layer, support structure, and mass transfer of boundary layers at membrane surface. As a comparison, the flow-rate diffusivity for the solute pass through the membrane is similar to the electricity current via any passive resistor. Consequently, the summation of $(1/B_s + 1/k_F + 1/k_D + K)$ can be considered the entire resistance of the membrane to solute transport influenced by the rate convection at bulk solutions.

It is important to mention as the mass transfer coefficient in PRO units with a way that have carried out by Hoek et al. to estimate the mass transfer coefficient of the feed/draw solutions, as shown in the following equation:

$$k_{\rm D} = 1.62 \left(\frac{u_{\rm D} D_{\rm D}^2}{d_{\rm h, D} L}\right)^{1/3}$$
 (24)

$$k_F = 1.62 \left(\frac{u_F D_F^2}{d_{h,F} L} \right)^{1/3}$$
 (25)

where $\mathbf{d}_{\mathbf{h},\mathbf{D}}$, $\mathbf{d}_{\mathbf{h},\mathbf{F}}$ are the hydraulic diameters for the draw and feed sides, respectively, $\mathbf{u}_{\mathbf{F}}$ are the cross-flow velocities, and $\mathbf{D}_{\mathbf{D}}$, $\mathbf{D}_{\mathbf{F}}$ are the diffusivity coefficients for both the draw and feed solutions, and L is the membrane length respectively (Hoek et al. 2002; Naguib et al. 2015).

METHODOLOGY

In this study, model was verified by identifying the physical properties of solutions, the membrane features, the permeability coefficients for water and salt, and the concentrations for feed and draw solutions as well as the reflection coefficient calculation as shown in the following sections. The accuracy and consistency of the developed simplified model were tested to distinguish its ability to specify water flux and salt reverse flux for simulation of the realistic FO/PRO process. Therefore, validation of this model is valuable and indispensable to determine its reliability. To do so, the bench-scale cross-flow process of FO/ PRO (taken from published article) was carried out at 20 °C with different modes of velocities (ranging from 0.103 to 0.207, 0.31, 0.414, and 0.465 m/s) (Bui et al. 2015). Sodium chloride (NaCl) was used as the draw solution and demineralized water was used as the feed solution. Additionally, the properties of both draw and feed solutions such as density, viscosity, diffusivity, and osmotic coefficient were taken from previous works. The experimental data of Bui et al., were employed to verify the model by using the iteration procedure algorithm loop together with the ECP/ICP moduli, structural parameter, and mass transfer coefficient at the operating conditions, as shown in Figure 2. The FO modes were used to measure the water flux by using the demineralized water (DI) as a feed solution. In FO, draw solutions of NaCl at different concentrations (0.5M, 1.0M, and 1.5M) were used. In PRO, NaCl concentrations (0.05 M, 0.5 M, and 1.0 M) were used as feed solutions, while a 1.5 M NaCl solution was used as the draw solution (McCutcheon & Elimelech 2006, 2008).



FIGURE 2. Algorithm loop of the simulation procedure to estimate water flux

RESULTS AND DISCUSSION

MODEL VALIDATION

According to the simulation following the algorithm loop, the model has been validated by comparing its results with experimental data of Bui et al. 2015. The percentage error for the data were calculated using the following equations below (Attarde et al. 2016; Juang et al. 2010) and tabulated in Table 2 (Appendix A):

Error%=
$$\left(\frac{1}{n}\sum_{n} \left| \frac{J_{w \text{ Exp. }} J_{w \text{ update Model}}}{J_{w \text{ update Model}}} \right| \right) \times 100$$

The average percentage error between the present model results and the experimental data is approximately 48% for FO and 21% for PRO. Therefore, the outcomes have revealed that there is good agreement between the model results and the experimental data of Bui et al. 2015 to predict the flux in PRO process, and this gives evidence that the model can be used for assessing the PRO process.

INFLUENCE OF THE REFLECTION COEFFICIENT ON THE WATER FLUX

Most studies have considered the reflection coefficient of the FO/PRO to be unity (Attarde et al. 2016; Bui et al. 2015). In fact, there is no ideal membrane, and therefore, the reflection coefficient can represent the intrinsic of rejected salt by this membrane. Figure 3 shows the effect of the calculated reflection coefficient on the computed water flux of PRO for different concentrations of NaCl (0.05M, 0.5M, and 1.0M) as feed solutions and a 1.5M NaCl solution as the draw solution. As a result of the reflection coefficient (σ), the figure clearly shows that any increase in the reflection coefficient led to an increase in the water flux with an augment in the cross-flow velocity.



FIGURE 3. Effect of the reflection coefficient on the PROwater flux with different velocities using the updated mod

Gradually, the increase in the reflection coefficient (σ) values at (0.05M as FS and 1.5M as DS) concentrations was (0.906, 0.927, 0.94, 0.95, and 0.953) associated with the increment in amounts of water fluxes (17.85, 21.96, 24.83, 27.39, and 28.13), respectively. These results were obtained as a result of the increase in the effective diffusivity of the solutes. As mentioned in the section of theory for this paper, the solute resistivity is a function of the mass transfer coefficient, that is, any increment in the mass transfer coefficients due to increase in the cross-flow velocity and leads to rise in the solute resistivity values as a result of partially inducing the mix up of the porous support layer. In addition, the figure clearly shows that the reflection coefficient ranges from 0.906 to 0.953, which means that the PRO process in terms of the water flux is more efficient with the increase in the value of the reflection coefficient. The higher value of the reflection coefficient implies a higher water flux the membrane that is denote to the membrane is a suitable to the process using NaCl concentrations as draw solution. In accordance with the definition of the reflection coefficient which represented, physically, the total resistance includes to solute resistance caused by the selectivity of membrane layer $(\frac{1}{B_{e}})$, mass

transfer of boundary layer at membrane sides $(\frac{1}{k_{r}}, \frac{1}{k_{p}})$, and the support layer (K), and by applying the Eq. (27 and 28) it can be showed in Appendix A (Table 3) that the predicted of solute resistivity (K) and mass transfer coefficients (k_F, k_D) for feed and draw solution at different conditions. It may be counted the summation of membrane resistivity and solutes resistivity to salts transport and this total resistance properly is induced by membrane structure and operating conditions. Thus, a high reflection coefficient (σ) signifies the high effective driving force in PRO processes resulting from the limited leakage of solutes from the draw solution to the feed solution. Thus, it is possible to consider the reflection coefficient as an indicator to evaluate the membranes, water flux, and the appropriate concentrations for the draw solution. As shown in Figure 4, the values of the reflection coefficient (σ) for the FO process were ascending, diverging at the same concentrations of the draw and feed solutions. The reflection coefficient varied from (0.868, 0.895, 0.908, 0.9152, and 0.918) with the feed solution DI and (0.5M, 1.0M, and 1.5M) NaCl concentrations for the draw solution at the difference in cross-flow velocity. It is obvious that the values of the reflection coefficient of the FO process are less than those of the PRO process. This signifies that the driving force in FO is lower than that in PRO as a result of the high leaky

solutes from the draw solution. Therefore, it can be inferred that there are influencing factors in the PRO process such as pressure applied on the system simulating the passage through the membrane, intrinsic property of the membrane, and also hydrodynamic conditions at the surface of the support layer. Therefore, the reflection coefficient (σ) could not be equal to 1, and its importance should be accounted for when modeling the FO/PRO performance using the draw solutions.



FIGURE 4. The reflection coefficient effect on FO-water flux using the updated model at the different velocities

ASSESSMENT AND COMPARISON OF THE PERMEATE FLUX FOR THE UPDATED MODEL

The performances for FO/PRO processes are evaluated in terms of the permeation flux by computing the water permeation flow-rate per unit membrane area and estimating the reverse salt leaking by determining the salt leakage per unit membrane area, respectively. Unlike the perfect state, many factors related to the incompetence of the membrane and module as a result of the convective and diffusive transport for the solute such as ECP, ICP, variation in concentration difference through the length of membrane module, and pressure losses in the module, may all decrease the performances of the FO/PRO processes. To show the comparison in the models, the updated model performance in terms of cross-flow velocity and water flux is shown in Figure 5 and Figure 6. Generally, the water and salt permeability coefficient Aw Aw and BsBs increase with the increase in the feed temperature, and its values at 20°C for HTI membranes are summarized in Appendix A (Table 1). These values were used in the updated flux model in Eq. (20) and (21), with the application of a procedure in Figure 2 for a simple algorithm loop iteration.



FIGURE 5. FO-water fluxes comparison between the updated model and previous model at the different

CROSS-FLOW VELOCITIES

Increase in cross-flow velocity led to increment in permeation flux of FO and PRO, as shown in Figure 5 and 6. This increment is due to the improved mass transfer coefficient as well as the diminishing ECP with dilutive and concentrative parameters for draw/feed solutions. The significant variation between the updated model and experimental rates of the water fluxes (5.4% to ~ 37% for FO/PRO) may be caused by different justifications such as membrane deformation in FO/PRO systems, where this membrane deformation possibly will lead to detrimental alterations in the transport parameters for membranes, besides the impact of the pressured applied in draw side of the system on the feed solution hydrodynamic. Therefore, it is difficult to realize the specific causes of this variation in the scale of the FO/PRO module.



FIGURE 6. PRO-water fluxes comparison between the updated model and previous model at the different

CROSS-FLOW VELOCITIES.

In this work, it can be suggested that the membrane deformation is a result of the thinness of the porous

(support) layer of the membrane that is commonly favored in designs of FO/PRO membranes so as to diminish the impacts of ICP and the increase in the flux across the module of the membrane (McCutcheon & Elimelech 2007; She et al. 2013). Therefore, in accordance with the RO operating philosophy, it is probably preferred that the thickness and strength of the porous (support) layer in the membrane are increased to eliminate the membrane deformation of PRO membrane structure. This may lead to an undesirable influence of ICP, and that results in a decrease in the performance of the PRO process. The use of different values for the cross-flow velocities resulted in different values of the solute resistivity, and that resulted in this variation in outcomes. Thus, it has better confirmation for a specific cross-flow velocity by applying an optimal cross-flow velocity for FO/PRO modules. The key of the PRO process is increment of the difference in solutions concentrations means increase in driving force of osmotic pressure and this lead to improve PRO performance by increasing water flux. According to the runs of the updated model, as shown in Figure 7, the selected orientation of this research is the active layer facing the draw solution (AL-DS), which is most widely used in PRO modules because it has the best performance with stability in the membrane. Three FS concentrations (0.05, 0.5, 1.0 M) were tested against one DS concentration (1.5 M), and the impact of the applied pressure on the PRO performance with effects on the water flux amounts can be observed. Gradually, at FS~0.05M against DS~1.5M, the water flux amounts represented by marker (\blacktriangle) escalated to reach a peak of ~26.24LMH with an applied pressure of ~9.25 bar, and then it began to descend to reach ~15LMH with 24 bar and so on due to increasing presence of salts diffusivity. The optimal range of applied pressure would be 9–13bar, which is approximately less than a quarter of the osmotic pressure of ~17bar (Achilli & Childress 2010; Anissimov 2016). On the other hand, the water flux represented by markers (\blacklozenge) and (\blacksquare) declined drastically in Figure 7. As a result, the reverse salt flux is at the convergence of concentrations. For FS (0.5, 1.0 M) and DS (1.5 M), the water flux was ~6.9 LMH accompanied by a peak optimal applied pressure range of $\sim 6-10$ bar at FS ~ 0.5 M and DS \sim 1.5M, whereas the water flux was \sim 2.5 LMH with a peak optimum applied pressure range of ~7-10 bar at FS ~1.0M and DS ~1.5M. This mostly leads to a reduced affectivity of the osmotic pressure in the membrane besides the appearance of the concentrative ICP. Furthermore, when operating in low pressure conditions and AL-FS orientation, the membrane appeared to be more stable in terms of the water flux and diffusivity of the reverse salt flux, which was responsible for the shift of the optimum applied pressure to lower values. Also, the ECP shows more effective at highly water flux, and for this reason, the

PRO process should be considered the required operation conditions such as lowering the applied pressure and cross-flow velocity.



FIGURE 7. Effect of the applied pressure on the amounts of water flux at the different concentration of FS and DS

IMPACTS OF SALT FLUX RATIO J_s/J_w

The specific ratio of salt flux J_s/J_w can be helpful in research by examining the effects of reverse salt flux on the performance of FO/PRO processes. The diffusivity of the reverse salt will occur together with the forward water passage at the same time, and this salt flux may result in the increase in ICP besides an increase in the bulk concentration of the feed solution, as well as induce an increase in fouling with the deformation of the membrane. Therefore, a higher salt flux is completely undesirable (Lee et al. 1981; Xiao et al. 2011; Yip et al. 2011; Zou et al. 2011). As it has been mentioned, the specific ratio of the salt flux J_{g}/J_{w} can be calculated using Eq. (18); it relies on two factors, which are water flux and pressure applied, considering that water and salt permeability coefficients are steady in short time scales. In Eq. (18), the expression $(1 + \frac{A_w \Delta p}{\cdot})$ is basic to study the impacts related with applied pressure and water permeability for the salt flux. Because the applied pressure is approximately equal to zero in FO modules, this means that Eq. (18) will become $(J_s/J_w) = B_s/(A_w i_v R_g T)$ in FO processes. In the PRO module, as shown in Figure 8, it can be noted clearly that the values of cross-flow velocities (0.1044, 0.207, 0.31, 0.414, and 0.465 m/s) correspond to an increase in the salt flux (1.7×10⁻⁴, 1.97×10⁻⁴, 2.16×10⁻⁴, 2.33×10⁻⁴, and 2.38×10^{-4} mol./m²s) at 1.5–0.05 M, whereas the salt flux diminishes relatively when the concentrations of the feed and draw solutions converge at 1.5-0.5M (9.23×10^{-5} , 1.04×10⁻⁴, 1.13×10⁻⁴, 1.21×10⁻⁴, and 1.24×10⁻⁴ mol./m²s); and salt flux values approaching to its effects less at convergent concentrations at 1.5-1.0M (6.63×10⁻⁵, 6.86×10⁻⁵, 7.05×10⁻⁵, 7.27×10⁻⁵ and 6.84×10⁻⁵ mol./m²s).

With this, it can be extracted that salt flux is directly related to water flux that implies any growth in salt flow-rate, and is essentially occurred by increasing in the permeation of water flow-rate. Also, in other indications clarified that the diffused draw solutes across membrane will be built up in the porous skin as a result of water permeation which passed on the inverse direction of flux. Then, the solutes will be accumulated inside the porous layer. Therefore, the

will be accumulated inside the porous layer. Therefore, the salt flux induced ICP causes a diminution in the activity of the driving force and thus a decrease in the PRO performance because of the diffusivity of reverse salts induced ICP, which is in addition to the ICP arising from the buildup of feed salts in the support layer.



FIGURE 8. Water flux and reverse salt flux at different crossflow velocities

An optimum amount relates to the ratio of specific salts flux J_s/J_w that designate the flow-rate of draw salts permeating through membrane module set up by water flux. As shown in Figure 9, the ratio of J_s/J_w is low at lower cross-flow velocities, which leads to reduce the quantities of salt flux. However, the effect of these velocity values on the boundary layer according to the relationship between the Reynolds number and boundary layer thickness and dilutive ECP appears at the membrane in the PRO process for the reason that salts are diluted at the local boundary layer in the surface of active layer (Prichard 2017). Thus, this will increase the ECP and its influence on membrane defacement by increasing of salt flux. In addition, it can be noted that the $J_{\rm e}/J_{\rm m}$ ratio is directly proportional to the ratio for the selected membrane B_s/A_w , and the estimations for the B_s and A_w values are relied on as steady during carry out the experiments. But regrettably, there are many experiments cited that changes of B_s and A_w values during the PRO process as a consequence of membrane variations that relied on the operation conditions (Kim & Elimelech 2013; Skilhagen et al. 2008). Because no perfect membrane, this mean inevitability of reverse salt flux in PRO modules because that is actually produced by elemental influences of PRO process and one of them is cross flow velocity. Referring to Fig. 8 and 9, it is possible to determine that the optimal

cross-flow velocity is 0.1044 m/s, which reduced salt flux with the increase in the water flux at the optimum applied pressure of ~13 bar. Consequently, in PRO modules, the diffusivity of salts must be controlled well and the B_s variation must also be minimal by developing the design of the membrane structure and spacer flexibility to avert the membrane damage and limit the risks affecting the membranes.



FIGURE 9. The specific ratio of J_g/J_w and salt flux at different cross-flow velocities

CONCLUSION

An updated model for the FO/PRO module is achieved with respect to the internal and external concentration polarizations, reflection coefficient, specific ratio of salt flux, and spatial differences for the membrane. The results show that the variations between the estimates obtained from both FO and PRO based on updated models relied on the veritable value for the reflection coefficient. The most important conclusions can be summarized as follows:

1. The model was validated to predict the PRO performance by testing it in FO and PRO modules using the experimental data from the previous work and corresponding concluding with PRO to acceptable deviation and error rates despite their variation, and it was noticed that can be used to predict the flux in the PRO modules, and since this model mainly relies on the applied pressure to drive the osmotic process, it is rarely used to predict FO performance.

2. The model was examined for the FO and PRO fluxes on the module and noted that have ranges of the reflection coefficient from 0.868 to 0.9 for FO and 0.9 to 0.95 for PRO for a NaCl draw solution, and so it is not possible to consider a value of the reflection coefficient equal to 1.0. as so its importance should be accounted for when evaluating the performance using NaCl as a draw solution.

3. The influences on the performance of FO/PRO were methodically studied in this paper such as: the concentrations

for feed and draw solutions; cross-flow velocity; the applied pressure; and the membrane model.

4. The resultant concentrations have different values of driving forces, and lower water fluxes with a low cross-flow velocity and vice versa in FO/PRO modules due to more detrimental concentration polarization were shown. As well as, this model was studied the performance of the membrane module with evolving a math-model to prophesy the performance, and it has been observed that the lower cross-flow velocity diminished reduced from reverse salt flux and decreasing values of the applied pressure which suggests a necessity for improvement the PRO modules with higher thickness and strength of the support layer steadiness.

5. It was concluded that the applied hydraulic pressure values are modified by relying on the structure and characteristics of the membrane used, as well as on the operational conditions of the modules, especially the cross-flow velocity. After applying this model. Upon to this, the Δp optimal was found as value ranging between 9–13 bar according to the operation conditions.

6. Since the model for this study is controlled by model variables such as the applied pressure, cross-flow velocity, and the specific ratio of the salt flux J_g/J_w , and on it have better to be a control to this ratio when it is used to evaluate the performance for the PRO-module. This ratio represents the balance between the fluxes of water and salts according to the variables of concentrations on the feed and draw sides as well as the operating conditions as a result to appear of ICP and ECP during the operation. It is found that the specific ratio of the salt flux for PRO augmented more severely at applied high pressure with the assumption of the fixed ratio of $B_{s.}/A_w$, which requires this ratio to be controlled in addition to improve the structure of the membrane.

ACKNOWLEDGEMENTS

The authors are grateful to the Universiti Kebangsaan Malaysia, Malaysia, University of Sharjah, United Arab Emirates and University of Al-Ameed, Iraq for support this research.

DECLARATION OF COMPETING INTEREST

None

APPENDIX A

TABLE 1. Physical properties of fluids, permeability coefficients for water and salt at the different temperatures and concentrations

Concentration (M)	Density (kg/m ³)	Viscosity*10 ⁻³	Diffusivity*10-9	B _s *10 ⁻⁷	$A_{w} * 10^{-7}$
		(Pa s)	(m ² /s)	$(m^3/m^2 s)$	$(m^3/m^2 bar. s)$
0	998.2	1.002	1.383	2.036	1.741
0.05	1000.3	1.007	1.329	2.036	1.741
0.5	1018.5	1.047	1.281	2.036	1.741
1.0	1037.8	1.092	1.301	2.036	1.741
1.5	1056.4	1.114	1.323	2.036	1.741

TABLE 2. Error percentage for the FO/PRO between updated model and the experimental pervious

Iteration	Velocity modes	FO-Model	PRO-Model	FO Expr.	PRO Expr.	% Error-FO	% Error-
No.	(m/s)	J _w (LMH)	J _w (LMH)	J _w (LMH)	J _w (LMH)		PRO
1	0.1044	11.116	17.85	5.1	13.7	54.120	0.2325
2	0.1044	16.916	5.95	5.81	7.1	65.653	- 0.1942
3	0.1044	20.166	1.98	6.6	2.25	67.272	- 0.1378
4	0.207	12.682	21.96	7	18.93	44.805	0.1381
5	0.207	20.200	7.79	7.1	8.24	64.852	- 0.058
6	0.207	25.011	2.32	7.6	2.5	69.613	- 0.0775
7	0.31	12.895	24.83	9.8	19.2	24.004	0.2269
8	0.31	23.749	9.03	10	9.73	57.894	- 0.0775
9	0.31	27.730	2.62	10.2	3.37	63.217	- 0.2868
10	0.414	13.186	27.40	10.5	20	20.372	0.2701
11	0.414	22.818	10.33	10.75	10.25	52.889	0.0075
12	0.414	29.139	2.94	11	4.2	62.250	- 0.4273
13	0.465	13.318	28.13	11.5	21.4	13.651	0.2393
14	0.465	23.271	10.73	12.1	11.5	48.005	- 0.0716
15	0.465	29.938	2.29	12.4	4.5	58.581	- 0.9632
						48%	21%

	k _b *10 ⁻⁵ (m/s)	2.129 2.151 2.175	2.175 2.175 2.175
0.465	k *10 ⁻⁵ (m/s)	2.24 2.24 2.24	2.181 2.129 2.151
	K*10 ⁵ (s/m)	3.45 3.45 3.45	1.50 1.50 1.50
	k _D *10 ⁻⁵ (m/s)	2.048 2.069 2.092	2.092 2.092 2.092
0.414	k _F *10 ⁻⁵ (m/s)	2.155 2.155 2.155	2.099 2.048 2.069
	K*10 ⁵ (s/m)	3.60 3.60 3.60	1.62 1.62 1.62
	k _D *10 ⁻⁵ (m/s)	$1.860 \\ 1.879 \\ 1.90$	1.90 1.90 1.90
0.31	kr *10 ⁻⁵ (m/s)	$1.957 \\ 1.957 \\ 1.957$	1.906 1.86 1.879
	K*10 ⁵ (s/m)	3.93 3.93 3.93	2.08 2.08 2.08
	k _D *10 ⁻⁵ (m/s)	1.625 1.642 1.661	1.661 1.661 1.661
0.207	kr *10 ⁻⁵ (m/s)	$1.711 \\ 1.711 \\ 1.711 \\ 1.711$	1.666 1.625 1.642
	K*10 ⁵ (s/m)	4.53 4.53 4.53	2.65 2.65 2.65
	k _D *10 ⁻⁵ (m/s)	1.294 1.307 1.322	1.322 1.322 1.322
0.104	k _F *10 ⁻⁵ (m/s)	1.362 1.362 1.362	1.326 1.294 1.307
	K*10 ⁵ (s/m)	5.95 5.95 5.95	3.60 3.60 3.60
How Velocity (m/s)	Concentration of Solution (M)	FS (0.0)/DS (0.5) FS (0.0)/DS (1.0) FS (0.0)/DS (1.5)	FS (0.05)/DS (1.5) FS (0.5)/DS (1.5) FS (1.0)/DS (1.5)
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TABLE 3

NOMENCLATURE

Aw	Water permeability coefficient.	(m/s Pa)
π	Osmotic pressure.	(Pa)
i _v	Van't Hoff coefficient.	-
C	Molar concentration of the salt.	(mol./l)
Rg	The universal gas constant.	(J/mol. K)
T	Absolute temperature of the solution.	(K)
IFO	Water flux pass via the membrane in forward osmosis.	m^3/m^2 s
L., PRO	Water flux pass via the membrane in pressure retarded osmosis.	$m^3/m^2 s$
Δπ	Actual (effective) osmotic pressure difference across the membrane.	(Pa)
W _n	The power density of the membrane.	W/m^2
Δp	the applied hydraulic pressure differential between draw and feed sides of the membrane.	(Pa)
π	Osmotic pressure for the draw solution at the surface of the membrane.	(Pa)
2,111	Osmotic pressure for the feed solution at the interface of the active-support layer, which is equal	
π _i	to C _{ian} .	(Pa)
Js	Reverse salt flux crossing through the membrane.	$(mol./m^2.s)$
Bs	Salt permeability coefficient.	(m/s)
ΔC	Difference in concentrations between the draw and feed sides for the membrane.	(mol./l)
C _{D.m}	Salt concentrations at the surface of the active layer of the membrane.	(mol./l)
C _{F.m}	Salt concentration at the surface of the support layer of the membrane.	(mol./l)
C _{D,b}	Salt concentration of the draw solution bulk.	(mol./l)
CF.b	Salt concentration of the feed solution bulk.	(mol./l)
K	Solute resistivity in the support layer.	(s/m)
D	Solute diffusion coefficient.	(m^2/s)
t,	Support layer thickness.	(m)
τ	Tortuosity of the membrane.	-
ε	Porosity of the membrane.	-
S	The structural parameter for the support layer.	(m)
δ _F	Boundary layer thickness at the feed side.	(m)
δ _D	Boundary layer thickness at the draw side.	(m)
$\pi_{D,b}$	Osmotic pressure of the bulk draw solution.	(Pa)
$\pi_{F,m}$	Osmotic pressure for the feed solution at the membrane support layer.	(Pa)
$\pi_{F,b}$	Osmotic pressure of the bulk feed solution.	(Pa)
σ	Reflection coefficient.	-
k _F	Mass transfer coefficient of the feed solution.	(m/s)
k _D	Mass transfer coefficient of the draw solution.	(m/s)
Sh	Sherwood number.	-
D_D, D_F	The diffusivity coefficient for the solute at the draw and feed sides.	(m^{2}/s)
dh	The hydraulic diameter for the flow channel.	(m)
Re	Reynolds number.	-
Sc	Schmidt number.	-
L	Channel length.	(m)
ρ	The density of solution.	(kg/m^3)
u	Cross velocity of solution.	(m/s)
μ	The dynamic viscosity of solution.	(Pa s)

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