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Factors affecting flux performance of forward osmosis systems

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ABSTRACT

The performance of a forward osmosis (FO) system may be characterised by the assessment parameters: FO–RO flux ratio ($J_w/J_{w(RO)}$), apparent FO water permeability ($J_w/(\pi_{ds}-\pi_{ml})$), and the newly developed flux efficiency factor ($J_{w,ob}/J_{w,re}$). The former two parameters offer information on extent of internal concentration polarisation and driving force utilisation, respectively. The $J_{w,ob}/J_{w,re}$ factor has practical relevance, and reveals the inevitable trade-off between flux and recovery (φ) for a FO system. The derived $J_{w,ob}/J_{w,re}$ factors corresponded well to experimental observations. High water permeability, low salt-to-water permeability ratio, and large mass transfer coefficient improve the performance of a FO system, but these may also be influenced by operational and fouling effects, such as draw solute transmission, fouling resistance and cake-enhanced concentration polarisation. It was shown that membrane properties also play a significant role in fouling behaviour. Fouling amelioration factors include aeration and osmotic backwash. A thin-film composite membrane showed potential for FO application with favourable intrinsic transport parameters. It was demonstrated that a FO system could achieve stable water production with both relatively high flux efficiency ($J_{w,ob}/J_{w,re}=0.8$) and high recovery ($\varphi=95.8\%$), which attested to the technology potential.

1. Introduction

Forward osmosis (FO) is a membrane system that technically exploits the natural phenomenon of osmosis, such that pure water from a feed water spontaneously flows through a semi-permeable membrane under an osmotic driving force provided by a draw solution. As a water technology, FO has been viewed with increasing interest due to a multitude of potential advantages that the technology offers. These potential advantages include [1,2]: (1) good product water quality comparable to conventional desalination technology such as reverse osmosis (RO), (2) no need for high hydraulic pressure, (3) high osmotic driving force attainable with suitable draw solution, (4) high recovery achievable, (5) low electrical energy demand possible with suitable post-treatment step using low grade heat, and (6) low fouling if foulant compaction is related to applied hydraulic pressure. In particular, the last attribute may find a niche for the technology to be applied in aggressive water environment with high fouling potential. This leads to the concept of integrating forward osmosis (FO) within a membrane bioreactor (MBR) setup, known as the osmotic membrane bioreactor (OMBR), that may be favourable for used water treatment and water reclamation application (Fig. 1) [3].

Recent studies have demonstrated the potential of OMBR as a FO system to produce high quality product water with low fouling tendency [4,5]. However, other studies have revealed that considerable fouling could still occur to FO systems under certain circumstances ([6,7] and this study). Investigation suggests that the low extent of fouling observed in some FO studies may be attributed to various factors at work, such as membrane orientation, level of flux, aeration and membrane surface and material properties [8,9].

The above discussion leads to a greater question of what are the factors that affect flux performance of a FO system. This question is of significance, because flux determines productivity, and ultimately, viability of the technology. Flux of a membrane system is largely influenced by both membrane intrinsic properties and fouling, which is complex [10]. For a FO system, it is an even more complex affair, due to the added intricacy of internal concentration polarisation (ICP). The ICP is a phenomenon inherent of the osmosis driven membrane system, and is due to hindered diffusion of solutes within the membrane support layer. In general, ICP acts to diminish the overall driving force across a membrane [1,11], but in some instances, it provides a self-compensating mechanism that could maintain relatively stable flux under fouling conditions [6,8]. Consequently, an analysis of flux in isolation would not be adequate to assess the various factors affecting the performance of the system.

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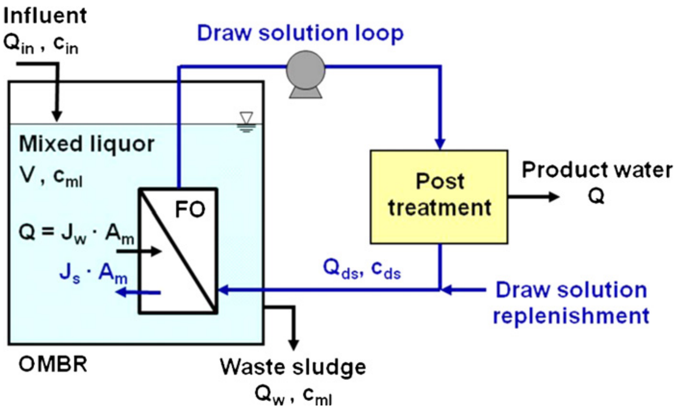

Fig. 1. Concept of osmotic membrane bioreactor (OMBR).

The goal of this study is to provide a platform for discussion of factors affecting the flux performance of a FO system. While the experimental studies were conducted on an OMBR, results and discussion from this study would be relevant for other FO systems too. Consequently, the term 'FO' is sometimes used interchangeably with 'OMBR' in this manuscript, depending on which term may be more relevant to the context. The study derived a simple theoretical framework with different methods to assess flux performance of a FO system. The methods were then systematically applied to modelled scenarios and experimental observations from six OMBR runs to obtain information on the system. This study focuses on flux performance of a FO system; discussion of other issues such as draw solute recovery and post-treatment is not covered in this study and can be found in [1,12].

2. Theoretical background

2.1. Flux equation for forward osmosis

A theoretical equation to model water flux for an osmosis driven system was originally developed by Lee et al. for a pressure-retarded osmosis (PRO) system [13]. The equation is valid for a FO system by setting the hydraulic pressure term to zero. Later studies built upon this concept and derived modelling equations for both FO and PRO systems [14,15]. However, most studies applied the analysis to well-defined feed and draw solutions, such that the effects of fouling under real operating conditions were not explicitly accounted for. For this purpose, Lay et al. [8] derived a fouling-incorporated water flux equation for a FO system based on resistance-in-series approach for a fouling condition with cake enhanced concentration polarisation (CECP). In this study, the same approach is adopted. It can be shown that the water flux of a FO system with membrane orientation of active layer facing feed water (AL–FW)—i.e. mixed liquor (subscript 'ml') for an OMBR–and draw solution (subscript 'ds') against the membrane support layer may be expressed as [8]:

$$J_w = A \cdot \left[\left(\pi_{ds} + \frac{B}{A} \right) \cdot e^{-(J_w/K_m)} - \left(\pi_{ml} + \frac{B}{A} \right) \cdot e^{(J_w/k_{CECP})} \right] \quad (1)$$

where A and B are the overall water and salt permeability coefficient and may be related to the respective coefficients of a membrane (subscript 'me') and fouling layer (subscript 'la') as follows:

$$\frac{1}{A} = \frac{1}{A_{me}} + \frac{1}{A_{la}} \quad (2)$$

$$\frac{1}{B} = \frac{1}{B_{me}} + \frac{1}{B_{la}} \quad (3)$$

It should be noted that the expression A may be equated to the hydraulic resistance (R_h) as originally given in Lay et al. [8] via the expression:

$$A = \frac{1}{\eta \cdot R_h} \quad (4)$$

where η is the viscosity of the permeating liquid. Furthermore, K_m is the mass transfer coefficient describing the ICP phenomenon within the membrane support layer, which may be described as:

$$K_m = \frac{D_{ds}}{S_{me}} = \frac{D_{ds} \cdot \varepsilon_{me}}{t_{me} \cdot \tau_{me}} \quad (5)$$

where D_{ds} is the diffusion coefficient of the draw solute and S_{me} is a structural parameter related to the structural properties of the membrane support layer, namely: thickness (t_{me}), porosity (ε_{me}) and tortuosity (τ_{me}) [16,17]. The expression indicates that K_m may be positively enhanced by a greater diffusion coefficient (e.g. increasing temperature or using more mobile draw solute) or a smaller structural parameter (e.g. thinner and more porous support layer) [1,16]. Note that the term K_m is sometimes regarded as the inverse of the resistance to solute diffusion within the membrane support layer [1,14]. However, in line with conventional mass transport literature [18] and membrane concentration polarisation concept [19], the term K_m will be used consistently throughout this study.

For the membrane orientation AL–FW, external concentration polarisation (external CP) takes place on the side of the membrane active layer. When no fouling occurs on the feed side and the flux is moderate, the effects of the external CP may be mitigated by fluid management and are typically subdued and comparatively small [13,20]. However, there are instances when the external CP effects could be significant. These may occur when the flux is significantly high [21], and/or a porous fouling layer has developed on the membrane surface, such that solutes diffusion within this fouling layer becomes severely hindered and cannot be mitigated by fluid management. In this instance, an elevated solute concentration may occur on the membrane surface, and greatly diminish membrane performance [22]. As noted above, this phenomenon is known as cake enhanced concentration polarisation (CECP) or cake enhanced osmotic pressure. It has been demonstrated that CECP can have dominant performance diminishing effect on a FO system, especially when this occurs in conjunction with reverse diffusion of draw solutes, culminating in an accelerated CECP mechanism [23]. Mathematically, CECP and ICP may be handled in a similar manner. The effects of CECP may be expressed via a mass transfer coefficient as follows [8]:

$$k_{CECP} = \frac{D_{ml} \cdot \varepsilon_{la}}{\delta_{la} \cdot \tau_{la}} \quad (6)$$

where D_{ml} is diffusion coefficient of the solutes within the fouling layer, and ε_{la}, δ_{la}, and τ_{la} are the porosity, thickness and tortuosity of the fouling layer, respectively. It should be noted that the above equation may also apply to non-fouling situations by setting $\varepsilon_{la} = \tau_{la} = 1$. In this instance, δ_{la} is the thickness of the boundary layer in accordance to the film model [19].

It should also be noted that a phenomenon of so-called cake reduced concentration polarisation (CRCP) has been reported [24]. This may occur for a denser fouling cake such that convection mechanism would be more hindered than diffusion mechanism. In this instance, the concentration on the membrane surface would be lower than what would be expected for a "normal" concentration polarisation, where convection ~ diffusion. Between CECP and CRCP, CECP would have greater and adverse effect on flux performance, and is modelled as a limiting condition in this study. However, contrary to RO systems, where CECP and CRCP may alter salt transmission [24]; this may not apply to FO systems with regard