Desalination 422 (2017) 5–16

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Review on methodology for determining forward osmosis (FO) membrane characteristics: Water permeability (A), solute permeability (B), and structural parameter (S)

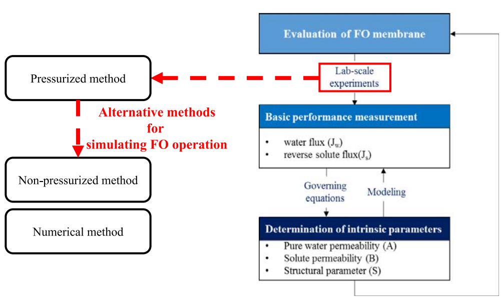
Bongchul Kim[a,b], Gimun Gwak[a], Seungkwan Hong[a,*]

[a] School of Civil, Environmental & Architectural Engineering, Korea University, 145, Anam-Ro, Seongbuk-Gu, Seoul, 02841, Republic of Korea

[b] Environmental and Plant Engineering Research Division, Korea Institute of Civil Engineering and Building Technology (KICT), 283, Goyangdae-Ro, IlsanseoGu, Goyang-Si, Gyeonggi-Do 10223, Republic of Korea

GRAPHICAL ABSTRACT

Evaluation system for forward osmosis (FO) membrane



ARTICLE INFO

Keywords:
Forward osmosis (FO)
FO membrane performance parameters
Water permeability (A)
Solute permeability (B)
Structural parameter (S)

ABSTRACT

Forward osmosis (FO) has attracted growing interest in both academic research and industrial development due to its fundamental and technical advantages. One of the key challenges that needs to be addressed to further advance this technology is the identification of an ideal membrane. However, the reliable methodology for characterizing FO membrane performance parameters has not yet been standardized, and thus various methods have been utilized to evaluate FO membrane performance. The RO-FO based method is the most widely used protocol, but it has fundamental problems in the measurement of intrinsic parameters. Non-pressurized methods have newly been suggested as another approach to evaluate FO membranes but they also have shown certain limitations, such as inaccurate performance prediction of pressure-applied FO processes. The development of a standard and reliable characterization method for FO membranes is an important step to enable the standardization of the results from different research works and to facilitate data exchange and interpretation. Process-optimized standardization method, which can accurately measure the intrinsic characteristics of the different osmosis processes, thus should be investigated in more detail through further research.

* Corresponding author.
E-mail address: skhong21@korea.ac.kr (S. Hong).

http://dx.doi.org/10.1016/j.desal.2017.08.006
Received 11 December 2015; Received in revised form 24 February 2017; Accepted 9 August 2017

1. Introduction

Forward osmosis (FO), an emerging technology for wastewater treatment and desalination [1–4], has attracted growing attention over the last decade in both academic research and industrial development [1,2,5–7]. In contrast to pressure-driven membrane processes such as reverse osmosis (RO), this process utilizes the osmotic pressure difference between two streams separated by a semi-permeable membrane to induce the mass transport of water into the higher osmotic potential draw solution. Compared to the conventional RO process, FO has demonstrated great promise in terms of reduced membrane fouling [6,8–11], lower energy requirements [1,3,7,9,12–14], and ease of membrane cleaning [1,9,12,13,15].

With the first study on FO released in 1976, hundreds of papers have been published in the past ten years. With many of these confirming the feasibility of the technique, FO has expanded its range of possible applications from food processing [6,7,15] and the desalination of high saline water [2,3,6,14] to shale gas waste water treatment [5,6,15]. Despite this potential, FO is still considered an immature technology because certain limitations have hampered its real-world implementation. A key challenge that remains to be faced is the identification of an ideal membrane [6,15]. To overcome this obstacle, a great deal of research has focused on the fabrication of FO membranes. This has resulted in the development of highly improved membranes tailored for the specific needs of FO.

As new FO membranes have been developed, many researchers have tried to quantitatively identify the characteristics of FO membranes. As a part of these efforts, several verification methodologies have been suggested, including a method for the assessment of apparent membrane performance: the measurement of pure water and solute fluxes [6,15–17]. This approach is not only convenient but also experimentally unconstrained, and thus has been widely adopted to define special features of newly developed and/or fabricated membranes. Table 1 summarizes membrane performance (pure water and reverse solute fluxes) and operating conditions reported in recent studies into FO membrane development. It can be seen that the experimental conditions, from the solutions used to membrane orientation, are inconsistent. As performance depends heavily on these operating factors, the lack of generality in this approach makes it difficult to compare membrane characteristics.

An alternative examination method – measuring the intrinsic parameters of FO membranes – has been proposed to assess the characteristics of membranes more impartially. Because a membrane's parameters do not change under typical test conditions, three performance indicators that together fully describe the characteristics of a particular membrane are the basis of this approach: (1) the pure water permeability coefficient, A, (2) the solute permeability coefficient, B, and (3) the structural parameter, S [6,16,17,62]. As illustrated in Fig. 1, these parameters can be used with individual governing equations for the accurate prediction of membrane performance in any lab-scale FO system. Accordingly, the values of A, B, and S represent common touchstones for the description of intrinsic membrane characteristics and offer a universal set of criteria for the direct comparison of performance, regardless of operating conditions.

Various approaches (e.g., pressurized and non-pressurized tests) have been suggested and used to determine these performance parameters, however, a standardized methodology has not yet been established [16,17,63,64]. As there has yet been no attempt to collect and analyze these various methods together in a single study, this paper presents a comprehensive review of the methodologies available to measure the characteristics of FO membranes. The review begins with an introduction of the intrinsic characteristics of FO membranes to provide a general understanding of the target performance parameters. Following this, a theoretical model based on the governing equations for performance prediction (i.e., pure water flux and reverse solute flux) is explained. Finally, the experimental and numerical methodologies used to measure FO membrane performance parameters are extensively reviewed.

2. Intrinsic characteristics of FO membranes

As illustrated in Fig. 2, most FO membranes are composed of an active and a support layer. The understanding of the FO membrane structure and characteristics is required first to develop the standard performance evaluation protocol. In this section, with a brief explanation of the structural properties of FO membrane, the conceptual meaning of the performance parameters is introduced.

2.1. Active layer

Because the active layer plays the role of selective transport barrier, FO performance, including water flux and reverse solute flux, is mainly determined by the inherent characteristics of this layer. The active layer is typically designed to be more exclusively selective towards water; in other words, it separates the water molecules while rejecting other solutes and pollutants from the feed solution.

The water flux is a result of the diffusion of water molecules across the membrane, with two important factors affecting the velocity of this transport: the magnitude of driving force and the selectivity of FO membrane on water molecules. As the driving force for water separation is quantified by the osmotic pressure difference, the water flux is determined by both this osmotic potential gradient and the intrinsic water selectivity of the FO membrane. So the water flux (J_w) can be expressed by the following equation:

$$J_w = A \cdot \Delta\pi \tag{1}$$

where A is the pure water permeability and $\Delta\pi$ is the osmotic pressure difference between the feed and draw solutions. As described in Eq. (1), the intrinsic selectivity of water molecules can be quantified by the pure water permeability (A). Therefore, the pure water flux increases proportionally with an increase in A.

Likewise, the diffusion of the solute through a FO membrane is driven by the difference in the solute concentration between the two separated solutions. Thus, the proportional constant of solute transport equation (Eq. (2)) can act as an indicator for the solute selectivity of a FO membrane:

$$J_s = B \cdot \Delta C \tag{2}$$

where J_s is the solute flux, B is the solute permeability and ΔC is the solute concentration difference between the feed and draw solutions. Note that the terms in Eq. (2) are all solute-dependent variables (i.e., The B value measured with NaCl may be different with one for $MgCl_2$.)

The solute in a FO system can diffuse in two directions with respect to its concentration gradient: forward feed and reverse draw solute diffusions. Forward diffusion occurs when the solute moves from the feed to the draw solution, while reverse diffusion occurs when the solute moves from the draw to the feed solution. Consequently, B should be minimized to reject unwanted salts and pollutants from the feed solution as well as to avoid the solute from the draw solution leaking into the feed.

2.2. Support layer

The support layer of a FO membrane is used to provide mechanical strength for the active layer; as a result, it tends to be thicker, more porous, and more tortuous. For this reason, unwanted phenomenon, diffusion hindrance of draw solute across the membrane support layer, occurs, thereby resulting in reduced membrane performance.

The quantification of this transport phenomenon is therefore greatly important for verifying the FO membrane performance, and the structural parameter (S) can act as a general yardstick for describing the characteristics of the support layer. The S is determined by the product