DESALINATION BY FORWARD OSMOSIS: FAILURE, SUCCESS, AND FUTURE EXPECTATIONS

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Contents

Summary

Water scarcity is one of the biggest concerns for humanity in the coming decades. Forward Osmosis (FO) is a natural process, driven by the osmotic pressure gradient across a semipermeable membrane. The process can be engineered to suit a variety of needs such as the production of clean, renewable energy, reusable water, fertigation, control release of drugs, high salinity wastewater treatment, seawater desalination and food concentration. Despite its immense potential, the technology has several barriers

preventing its commercialization. FO membrane is the major component of the capital cost and considered as a critical obstacle that may affect the application of the FO commercially. The current cost of the FO membrane is around 4.5 times higher than the RO membranes, primarily due to the lack of demand for the current FO membranes. Another barrier is the lack of an ideal Draw Solution (DS) that can easily be recycled. Technically, no draw solution has been found till date, which satisfies the ideal draw solution requirements for the FO process. The search for an ideal draw solution seems to be a holy grail in the FO process.

Several drawbacks of the FO process includes concentration polarization, fouling, and reverse salt diffusion. Concentration polarization occurs in all membrane processes; however, in the FO process, a unique phenomenon known as internal concentration polarization occurs, which reduces the water flux dramatically. The reverse salt diffusion exacerbates the process from the draw solution to the feed solution. Both internal concentration polarization and reverse salt diffusion only occur in the FO process.

This chapter will introduce the reader to forward osmosis technology. After a brief introduction, an overview of the desalination process, draw solutions, and transport mechanism in the FO process will be discussed. The various drawbacks of the FO process are also discussed in depth. The current successful applications of the FO technology will be discussed along with future applications and future directions.

1. Introduction

Forward osmosis technology has received significant attention from scientists and researchers for potential use in water purification and desalination processes. It is one of the most investigated technologies in water engineering with a large number of research outputs. The feature of water extraction from feed solution, using a concentrated ionic solution, is an attractive concept in membrane processes. Osmotic pressure is the driving force in the forward osmosis process instead of hydraulic pressure in the Reverse Osmosis (RO), and hence ions-solvent separation would be achieved at low energy. Since no hydraulic pressure is required, the forward osmosis process would ensure significant energy and capital cost saving.

Despite the great potential of the forward osmosis technology and a large number of research outputs, the technology is still in the early stage of commercialization. There are only a few pilot plant studies for technology demonstration and small commercial plants for indirect desalination and wastewater treatment. The reason for the late commercialization of the forward osmosis process is that researchers and scientists overestimated the process performance, which gave the wrong impression about the technology potential. Lacking proper membranes for the forward osmosis process, membrane cost, and using costly draw solutions or toxic draw solutions were among the reasons for failing the early commercialization of the forward osmosis process. Also, the cost of the regeneration process was overlooked, and most early research was focusing on the performance of the forward osmosis process. Nevertheless, forward osmosis is still recognized for potential use in the treatment of low-quality feed solutions, or when the regeneration process is already in place.

1.1. Water Shortage: A Brief Description of Water-Stressed Regions and Availability

Across the different continents of the world, the demand for freshwater is on the increase exacerbated by a growing world population, depletion of natural resources, industrialization, climate change, amongst other factors outlying water management, including geopolitics, demography, technology, societal values, governance, and law. As a result, water bodies such as rivers, lakes etc. are drying or being polluted. From the perspective mentioned above, it is also noteworthy to address water scarcity as one of the major global challenges in the 21st century. An alarming report by the United Nations Organization depicted that an estimated 2.8 billion people across the globe will be under serious water scarcity by the year 2025. Water scarcity is known as the combined effect of human-made and natural phenomena, which affects every continent and has a direct impact on the ecosystem and human life. Agriculture and industries based production are totally dependent on the availability of water, which has a huge influence on poverty and food security. Water for agriculture and industrial production have huge pressure on the availability of freshwater resources. Irrigation use accounts for approximately 70% of global freshwater withdrawals. Furthermore, industries consume relatively less water on a global scale when compared with irrigation, yet industries require an accessible, reliable, and environmentally sustainable supply of pure water. With a rapidly diminishing access to freshwater resources and given a much more preponderance of oceanic saltwater resources relative to the other available water resources, attention is now being focused on the desalination of salty seawaters to obtain adequate freshwater. For this reason, numerous international institutions and governments all over the world have promoted research and development projects for the sustainable and efficient production of clean water using seawater and wastewater. In this regard, capitalizing on sustainable and environmentally friendly purification of water can potentially retard the water scarcity problem and at the same time can help the world to fight against global climate change.

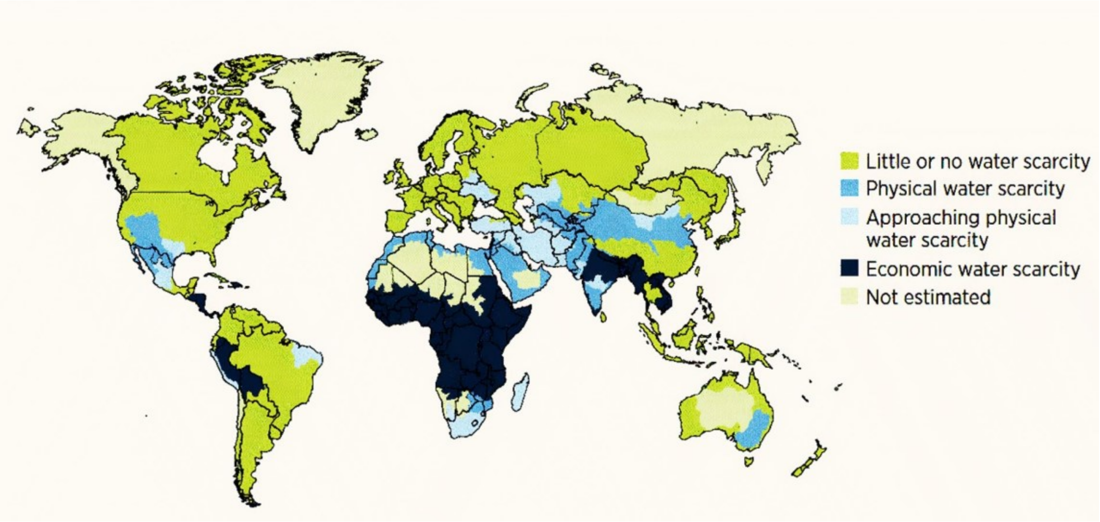

Figure 1. Global physical and economic water scarcity in 2025, Source: World Water Assessment Programme (WWAP), March 2012.

1.2. Desalination Processes

Amongst the different viable technologies for desalination are pressure-driven, thermal driven, and electricity-driven processes. Pressure-driven membrane processes include mainly RO, nanofiltration (NF), microfiltration, ultrafiltration (UF), and also a relatively new technology known as Pressure-Assisted Forward Osmosis (PAFO). These technologies, especially RO and NF processes, have dominated the desalination market for decades and are the most efficient and widely used all over the world. The principal driving force behind pressure-driven processes is hydraulic pressure, which is used to force water through a semipermeable membrane, leaving a brine to reject or concentrate behind and pure water as the output product. In practice, RO membranes have a pore size of 0.0001 to 0.0005 micron and have the ability to reject 95-99% of the pollutants in the feed stream. The typical pressure range for RO is 100-800 psi (pounds per square inch). RO membranes have high mechanical strength and are designed to withstand such high hydraulic pressures. NF membrane, on the other hand, has a pore size of 0.1 to 10nm (nanometre) and provides high rejection for multivalent ions such as calcium, magnesium, and lower rejection for monovalent ions such as sodium and chloride. The main advantage of NF compared to RO is that it can operate at lower hydraulic pressure, and more flexibility in terms of ion rejection, so that it can be tailored for processes that require certain ion rejection. The pore size of pressure-driven membranes processes and the hydraulic pressure requirement increases in the order MF>UF>NF>RO as presented in Table 1. Despite the efficiency of pressure-driven processes, they suffer from several drawbacks such as high energy requirements, require extensive pretreatments, and higher capital and operating costs. Unfortunately, the costs of RO desalination is still unaffordable in many countries.

	Microfiltration	**Ultrafiltration**	**Nanofiltration**	**Reverse Osmosis**
Pore size (μm)	0.1	0.01	0.001	<0.001
Pressure (bar)	0.1-1.0	1-10	10-30	20-80

Table 1. Order of pore size of pressure-driven membranes

Apart from pressure-driven membrane processes, other key players in the desalination industry are thermal processes such as Multi-Stage Flash (MSF), Multi-Effect Distillation (MED), and Mechanical Vapor Compression (MVC). Thermal desalination accounts for about 50% of the entire desalination market (Ettouney, 2009). Thermal processes such as MSF and MED are widely used in gulf countries and are the leading processes in thermal desalination. Amongst all the thermal processes, a low-temperature horizontal tube MED also termed as LT-MED, is thermodynamically the most efficient of all thermal processes (Ophir and Lokiec, 2005). MED can make desalination very economical if a source of waste heat or zero cost heat is available as an input to the MED plant. MSF, on the other hand, is considered an energy-intensive process compared to the MED process, as it requires higher operating temperature compared to the MED. However, MSF plants can be suitable for applications where abundant solar energy is available. Recently a new thermal process known as Membrane Distillation (MD) has emerged in the desalination industry. The driving force behind MD is the water vapor difference and a partial temperature difference between a hot saline feed solution and a cooler permeate. During the MD process, a hot saline feed is brought in contact with a porous hydrophobic membrane. The membrane acts as a barrier to the liquid flow, and only allows water vapor diffusion. A critical failure of the MD process is membrane wetting, which results in leakage of the saline feed solution to the permeate side (Warsinger et al, 2017).

A new osmotically driven membrane process, forward osmosis (FO), has also attracted tremendous interest from researchers and scientists across the globe as one of the promising membrane processes and a possible alternative to the RO process. The significant advantage of FO over other pressure-driven membrane processes is that FO phenomena occurs spontaneously, and requires no hydraulic pressures. The FO process will be discussed in more detail in the following sections.

2. Introduction to Forward Osmosis

Water is the most important resource that human beings need to live. Given the exponential growth of the population during the last decades, it is necessary to find an economical and safe way for the environment to guarantee drinking water for the population. In light of this information, the demands for new purification and desalination technologies such as the forward osmosis process is required. Forward osmosis is a phenomenon that produces a flow of freshwater from a low concentration or diluted solution to a high concentration solution or stream through a semipermeable membrane of high water permeability and reject rate to ions. Freshwater transport in the FO process is due to the osmotic pressure difference across the membrane. The high concentration solution is known as a "draw solution" or the extraction solution, and the low concentration solution is usually called "feed solution" or the donor solution. At the end of the FO process, the concentrated stream becomes diluted while the diluted feed stream becomes more concentrated due to the loss of freshwater.

2.1. Principles and Applications

FO uses an osmotic pressure gradient to permeate water from a solution of low solute concentration (also known as feed solution or FS) through a semipermeable membrane towards a solution of high solute concentration (also known as Draw Solution or DS). The osmotic pressure is generated by the solution of high solute concentration or draw solution (Figure 2). Unlike the RO process, the FO process uses the osmotic pressure difference ($\Delta\pi$) instead of the hydraulic pressures (ΔP) for freshwater extraction from the feed solution. The hydraulic pressure ΔP is almost zero in the FO process, which eliminates the need for high-pressure hydraulic pumps and duplex stainless steel tubing as required by pressure-driven membrane processes such as RO.

The water passage J_{w} across a membrane is given by

$$J_{\mathrm{w}} = A\sigma\Delta\pi \ , \tag{1}$$

where A (L m^{-2} h^{-1} bar^{-1}) is the pure water permeability coefficient of the membrane used in the forward osmosis process, and σ is the reflection coefficient and is assumed as 1 in FO experiments due to its high rejection rates. Most commercial FO membranes have a rejection rate of 95-98%. Thus, Eq. (1) becomes

$$J_{\mathrm{w}} = A\Delta\pi \,. \qquad (2)$$

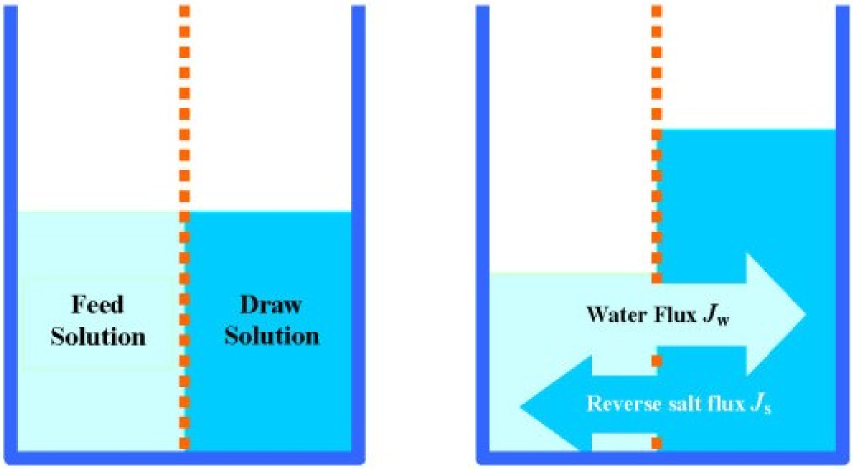

Figure 2. Forward osmosis process

Equation (2) describes water flux across the membrane; however, it over-estimates the water flux by almost 50%. This is mainly because Eq. (2) neglects the impact of concentration polarisation phenomena across the FO membrane. We will discuss concentration polarisation in detail in the subsequent section. Equation (2) can be further simplified. The theoretical water flux in the FO process is driven by the difference of osmotic pressure between draw solution and feed solution and is given by Eq. (3).

$$J_{\mathrm{w}} = A(\pi_{\mathrm{db}} - \pi_{\mathrm{fb}})\,, \qquad (3)$$

where π_{db} and π_{fb} are the bulk osmotic pressures of the draw solution and feed solution, respectively. Experimental water flux in the FO process can be determined analytically by using Eq. (4)

$$J_{\mathrm{w}} = \Delta V / A_{\mathrm{m}}\Delta t \;. \qquad (4)$$

ΔV is the change in feed solution volume over the interval of time (Δt), and A_{m} is the effective membrane area (m^2) of the FO membrane. Equation (3) shows that the FO process only relies on the osmotic pressure differences between the feed and the draw solution and the water permeability constant of a membrane. Due to the osmotic pressure gradient, water flows from the feed side to the draw side, and the draw solution becomes diluted. An additional step is required to separate the freshwater from the draw side if clean water is desired as the final product.

Along with the water flux across the membrane from the feed to the draw side, there is back diffusion of salt from the draw side to the feed side and is called reverse salt flux as indicted by J_s in Figure 2. Reverse salt flux is a major issue in the FO process, and it occurs when salt from the draw solution side permeates the feed solution and hence results in a decrease in net osmotic pressure across the membrane. In the FO process, the solute diffuses in two directions, or a bidirectional solute flux occurs. Mathematically, the diffusion of solutes through a semipermeable membrane is given by Fick's law

$$J_s = B\Delta C, \qquad (5)$$

where B is the solute permeability coefficient (L/m2h), and ΔC is the difference of solute concentration across the membrane. This reverse salt diffusion, as shown by Eq. (5), causes a decrease in the net driving force across the membrane and hence causes a reduction in the water flux from the feed to the draw side. An ideal draw solute in the FO process, therefore, should have osmotic pressure high enough to promote a high water flux across the membrane as well as smaller reverse salt flux.

FO has wide application to date in seawater desalination and wastewater treatment. Desalination with the FO processes consists of two stages; extraction of freshwater and dilution of the draw solution stage and freshwater extraction and regeneration of the draw solution stage. At the end of the first stage of the FO process, pure water is not obtained, but a mixture of freshwater and the osmotic agent is the product. For this reason, it is necessary to carry out a separation mechanism to remove the osmotic agent and obtain water suitable for human consumption or reusable for other processes. The quality of the permeate produced by the FO process is close to that of RO and superior to that of microfiltration and ultrafiltration (Zhang et al. 2017). In wastewater treatment applications, in particular, the FO process has tremendous potential. The biggest advantage of FO in treating wastewater is its low fouling propensity. Wastewater has low osmotic pressure than seawater but has higher fouling propensity. Therefore FO is ideal for treating complex wastewaters (Zhao et al. 2012). To cause an optimal flow of water in the system, a high osmotic potential is required to exceed the potential of the wastewater to be treated. It is important that the draw solution is not toxic, can be easily recovered once it is concentrated, and it should not cause deterioration of the osmotic membrane bioreactor if there is a bioreactor in the treatment system so that it does not affect the quality of the sludge or the growth of microorganisms. Transport properties will also be significant when choosing a draw solution. For example, large molecules have less diffusivity and filter more slowly through the membrane than small ones. Other factors to take into account are pH and temperature, especially to avoid scaling due to calcium, sulfate, or carbonate precipitation. In the specific case of wastewater as a feed solution to the FO system, certain researchers have proposed magnesium chloride as a draw solution due to its high efficiency and easy recycling by the nanofiltration process.

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Biographical Sketches

Dr. Ali Altaee is a Senior Lecturer at the University of Technology in Sydney. He completed his BSc, MSc, and PhD specializing in civil and Environmental Engineering. He has industrial and academic expertise through working at industrial research centres and institutes of higher education. He was a key member in the team which has developed the world-first pilot plant for water purification using osmotic energy at Surrey University; the project received the Queen's Anniversary Award for research in 2011. Dr. Altaee has worked on the development of a new concept for power generation from a potential chemical gradient which has been recognized as a novel technique for power generation using membrane technology. His innovative research outcomes have also resulted in the development of low energy treatment technique of seawater for the thermal evaporator, which is currently in the stage of commercialization.

Ibrar Ibrar is currently a Ph.D student at the University of Technology in Sydney. He completed his MSc from Anglia Ruskin University, UK. He is working on the "forward osmosis process" under the supervision of Dr. Ali Altaee. He is mainly working on concentration polarization modelling and mitigation of fouling using novel antifouling products.