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Water desalination by forward (direct) osmosis phenomenon: A comprehensive review

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HIGHLIGHTS

- An updated review of forward osmosis is provided
- Water and reverse solute flux models are reviewed
- Fouling and other challenges are addressed
- Strengths and limitations of the applications of FO are discussed
- State-of-the-art of the physical principles, recent developments, and applications of forward osmosis are reviewed

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ABSTRACT

Forward osmosis (FO) is a developing technology, which is thought to have a potential of producing potable water in an energy-efficient manner. FO is driven by the natural osmotic pressure difference across a semi-permeable membrane. Despite a number of patents and peer-reviewed papers published for different methods and systems for water desalination by FO, this technology is still in its infancy because of some serious limitations and challenges. Due to many environment and energy related challenges, FO-based desalination has recently gained worldwide attention because it operates at low levels of pressure and temperature. Compared to traditional pressure-driven membrane processes, FO offers recognized advantages including reversible membrane fouling, and potentially less operation energy.

The purpose of this review paper is to provide the state-of-the-art of the physical principles, recent developments, and applications of forward osmosis in the area of water desalination. Strengths and limitations of the applications of FO processes in the area of water desalination are highlighted and the future of FO technology is considered.

Contents

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1. Introduction

Water scarcity has become a global risk and one of the most serious concerns for the scientific community as a result of increasing population, continuing industrialization, expanding agricultural activities, increasing inequities between water supply and demand, improper management and degradation of natural water resources, and increasing regional and international conflicts [1–8]. Recent statistics show that approximately 15% of people around the world lack access to drinking water and 36% of the world's population suffer from water scarcity for at least one month of a year [9]. In the last century, water demand and its use have been increasing at a rate twice the rate of population growth [10]. In fact, statistical forecasts and predictions show that two-thirds of the world's population may be subjected to water stressed conditions by the year 2025 which will not only impede the socio-economic growth but also pose threats to our healthy ecosystems [1,11].

In order to supplement the global supply of pure water, the water industry today greatly relies on desalination of seawater. However, due to inextricable link between water and energy, the conventional desalination technologies such as multistage flash evaporation (MSF) and reverse osmosis (RO) have been considered energy-intensive and costly due to high energy consumption and increasing energy costs [12–17]. As a result, researchers are continuously exploring energy-efficient and less costly technologies to desalinate seawater. Over the last decade, forward osmosis (FO) has been considered by various researchers as an energy-efficient and economical alternative to the conventional seawater desalination technologies [18–21]. Besides seawater desalination, the FO process has been applied in wastewater treatment [21–38], food processing [20,39–44] and power generation [45–58]. Fig. 1 depicts the growing research interest in FO by showing the total number of journal articles and patents that have been published annually between the years 2005 and 2014. However, few review papers on FO appear in the literature [20,21,59–61].

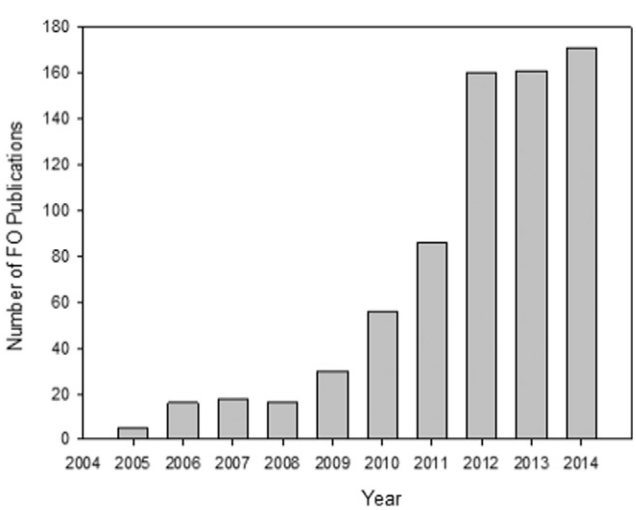

Fig. 1. Increase in number of forward osmosis (FO) publications (journal articles, conference papers, and patents) between the year 2005 and 2014 (retrieved from Google Scholar database search).

This review paper outlines the physical principles and theory of FO desalination and provides an updated and comprehensive review of the draw solutions and membrane developments in the area of FO desalination. Strengths, limitations and challenges of the applications of FO processes in the area of water desalination are also highlighted and the future of FO desalination technology is discussed.

2. Forward osmosis desalination

2.1. Physical concept and phenomenon

The concept of osmosis has been known to mankind since the beginning of human civilization. The physical phenomenon of forward osmosis (FO) can simply be defined as the movement of water molecules across a semipermeable membrane due to difference in osmotic pressure driving force across the membrane. The semipermeable membrane allows only water molecules to permeate through while the solute or salt molecules are rejected. The FO desalination process simply makes use of a highly concentrated salt solution (known as the draw solution, osmotic agent, osmotic media, or osmotic engine) with low water chemical potential (high osmotic pressure) to draw the water molecules from a feed solution (brackish or seawater) with higher water chemical potential (lower osmotic pressure) compared to the draw solution. This is in agreement with the 2nd law of thermodynamics, since transport of water molecules will bring chemical potentials in the feed and the draw solution to equilibrium.

During the FO process, the membrane rejects the salts and consequently, the feed solution is concentrated and the draw solution is diluted with time. Pure water has then to be recovered from the diluted draw solution by using an energy-efficient separation technique. Unlike RO, FO utilizes the natural osmotic pressure difference across the membrane to transport the water molecules and does not require application of hydraulic pressure to overcome the osmotic pressure of the feed. A comparison of water flux direction in FO and RO is shown in Fig. 2. In short, the process of FO desalination can be divided into two steps. In the first step, water molecules are permeated from the feed to the draw solution across the semipermeable membrane. In the second step of FO desalination, the draw solution is subsequently recovered by separating pure water from the diluted draw solution obtained in the first step of the