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Chapter 1

Reverse osmosis

1.1 INTRODUCTION

Fresh water is essential for human life [1, 2]. Securing fresh water is one of the most important issues for humankind. However, human population has increased steadily, and millions of people are concentrated in metropolitan cities [3, 4]. The amount of natural freshwater is insufficient to meet the demands of the population [5]. Thus, fresh water must be produced from saline water resources to extend the capacity of the water supply. Desalination is defined as a methodology that removes/separates minerals and ions from saline water to obtain fresh water [6]. Therefore, the type and amount of dissolved minerals and ions in the feed water are very important for determining the appropriate desalination methodology. For example, seawater contains many minerals and ions that are very minute in size. Therefore, it is not sufficient to separate seawater to produce freshwater by using a simple filtration step such as microfiltration (MF) or ultrafiltration (UF). Thus, the characteristics of each desalination methodology should be considered to determine the appropriate method for each feed water type.

Desalination is usually conducted using two methodologies for separation: thermal-based desalination and membrane-based desalination. Before advances in membrane desalination technology, thermal-based desalination was widely utilized because it has many advantages, such as easy adaptability and producibility of high-quality freshwater. Humans have been supplying freshwater from saline water using thermal-based desalination for thousands of years. To satisfy the production capacity with increasing human population, this traditional method has been developed for advanced thermal desalination technologies such as multistage flash (MSF) and multi-effect distillation

(MED) [7]. Over the past several decades, with the development of membrane technology [8], membrane-based desalination has attracted the attention of many researchers due to its many advantages, such as easy scale-up and low energy consumption [9]. Many membrane-based desalination technologies, such as forward osmosis (FO), reverse osmosis (RO), capacitive deionization (CDI), and electrodialysis (ED), have been developed [10]. Among these membrane-based desalination technologies, RO has been regarded as one of the most widely utilized desalination technologies for freshwater production [11–14]. The increased preference for RO is obvious for seawater desalination. It can be clearly identified that the capacities of installed RO plants for seawater desalination were much higher than 65% of the overall installed capacities for seawater desalination in 2013 [15]. The overall price of desalination systems has been reduced. Therefore, it is expected that desalination capacity will continuously increase [9]. Under these circumstances, RO systems are a major technology for the utilization of seawater desalination.

Low energy consumption is the most attractive advantage of RO systems for seawater desalination [16, 17]. The main reason RO systems consume lower energy than thermal-based desalination is that phase transition is not required for the separation from feed water to permeate water (freshwater) and concentrated brine. Meanwhile, the energy consumption and the required operating pressure in the RO system are directly correlated with the feed water concentration [11, 12]. Therefore, it is important to consider the feed concentration for RO system design.

The water resources on Earth are classified according to the feed concentration. Brackish water, which is defined based on its range of salinity between seawater and freshwater, includes river water, groundwater, and surface water [18]. The concentration of brackish water was the lowest among the other water resources. Thus, the energy consumption required for the separation of brackish water was the lowest. The low energy consumption makes brackish water desalination technologies attractive because freshwater can be supplied at an affordable price [11, 12, 19, 20]. However, brackish water resources are insufficient to supply all human populations [9, 21]. Thus, it is inevitable to find more abundant water resources for a sustainable supply to human society.

Hypersaline water is defined as saline water containing higher concentrations than seawater, so it has a very high osmotic pressure because of its high concentration. The high osmotic pressure becomes a technical barrier for treating hypersaline water by RO because a very high operating pressure should be applied to the feed solution. This pressure required for hypersaline water treatment often exceeds the pressure limitation of commercial SWRO membranes of less than 81 bar [22, 23]. In addition, the high energy consumption for the treatment of hypersaline makes the hypersaline water desalination infeasible technology because it is not economically favorable compared to other water resources such as brackish water and seawater [24–26]. However, many SWRO plants discharge large amounts of highly concentrated brine, causing significant environmental problems [27]. Therefore, the requirement of brine treatment systems for zero liquid discharge (ZLD) has increased, and hypersaline water treatment by RO has been investigated by many researchers [22, 25, 28]. In addition, since shale gas produced water [29, 30], landfill leachate [31], and flue gas desulfurization wastewater [32] contain very high salinity, effective technologies for the treatment of these types of high-salinity water should be developed. Recently, many new RO processes, such as draw solution assisted RO [33], osmotic-enhanced dewatering [29, 34], and osmotically assisted RO [35] have been developed. These processes can change from a single-stage RO system applying high pressure to a two-stage RO system with low pressure. Therefore, these processes can be effectively used to treat hypersaline water. Nevertheless, the high energy consumption and high cost are major barriers that prevent hypersaline water desalination from being widely utilized as a main water resource for water supply.

Seawater accounts for more than 97% of all water resources on Earth. In water-scarce regions such as the Middle East and North Africa (MENA), seawater desalination is regarded as a permanent solution for water scarcity problems [36, 37]. In these regions, the need for desalination is tremendously increasing [38], and desalinated water is not only used for drinking but also for irrigation and industries [39]. It has been reported that recently installed large-scale SWRO plants can produce freshwater at prices lower than \$0.5/m^3 [40], which is significantly lower than the price of thermal-based desalination and much lower than the price of SWRO plants 30 years ago (higher than \$2/m^3) [9]. This has led many policymakers and stakeholders to invest in SWRO technology for desalination systems [9, 36, 37]. However, although the energy efficiency of SWRO is the highest among other desalination technologies with high technological maturity [41], it is still necessary to reduce the energy consumption further because the overall desalination capacity installed worldwide is more than 90 million m^3/day [36], and it is expected that the overall energy consumption in all desalination plants will continue to increase consistently. The specific energy consumption (SEC) of the SWRO process has been decreased from 20 kWh/m^3 (in 1970) [42] to only 2.5 kWh/m^3 (in 2010) [21, 43] by developing high-efficiency energy recovery devices (ERDs) [11, 44–46], energy-efficient high-pressure pumps [47–50], and high-performance RO membranes [51–54]. However, the energy consumption of the SWRO process might be reduced further given that the theoretical minimum energy for separation of seawater with a salinity of 35 000 mg/L is approximately 1.07 kWh/m^3 at 50% recovery [21, 45]. In addition, the SWRO process uses a very energy-intensive system [36]. Therefore, it is crucial to minimize the energy consumption of the SWRO system to reduce energy loading in the energy supply system. Recently, global energy crisis has emerged as a major issue, and under these circumstances, low energy consumption in seawater desalination has become very important, and many researchers and engineers have been working to develop innovative ways to minimize the energy consumption of the seawater reverse osmosis (SWRO) process. In addition, the electrical energy required to operate most SWRO plants is supplied by fossil fuels [37]. As power generation by fossil fuels is correlated with greenhouse gas emissions [55, 56], the energy efficiency of SWRO plants needs to be improved for sustainable water supply by desalination systems.

In summary, RO systems for seawater desalination are the most viable technologies for sustainably securing freshwater resources; however, the most recent significant issue in RO systems is energy minimization. RO was developed as an advanced technology for desalination, and research and development to improve the RO system will continue in the future. Recent developments in RO systems have focused on improving energy efficiency for desalination in various feed solutions. In this book, we comprehensively cover the energy consumption issues in the SWRO system from a fundamental understanding to the analysis of the improvement strategy for energy minimization in the future. In Chapter 1, the definitions of osmotic pressure and RO are included to explain the SWRO system. Chapter 2 presents a detailed configuration of existing SWRO plants and the characteristics of each unit process. From the intake to the discharge, all the system units for the SWRO plants are covered in this chapter. In Chapter 3, the methodology for calculating the energy consumption in the SWRO process in a large-scale system is explained. Current energy trends in the SWRO plants, and the manner in which the energy consumption in the SWRO has been reduced are described in Chapter 4. In Chapter 5, the main factors affecting energy consumption are identified from the actual SEC data from the installed SWRO plants, and future strategies for further improvement of energy efficiency are introduced. The actual applicability and future potential of each strategy are discussed in Chapter 6. State-of-the-art technologies for each improvement strategy are also introduced.

1.2 DEFINITION AND OSMOTIC PRESSURE

A semi-permeable membrane allows solvent molecules to freely permeate the membrane, whereas solute molecules do not. When two solutions containing different solute concentrations are separated by a semi-permeable membrane, the net water flux across the semi-permeable membrane is in the direction from the highly concentrated solution to the low-concentration solution by osmosis [57]—the net water flux decreases as the level difference between the two solutions increases. Eventually, there is no net water flux across the membrane at equilibrium, as shown in Figure 1.1. In this situation, the osmotic pressure difference can be measured by the pressure difference arising from the level difference between the two solutions. The osmotic pressure difference becomes larger if the concentration difference between the two solutions is larger. To produce water permeate flux from the highly concentrated solution to the low-concentration solution, a pressure higher than the osmotic pressure difference should be supplied to the solution containing a high concentration. In other words, the osmotic pressure is a hurdle (for water molecules in the highly concentrated solution) to permeate in getting into the low-concentration solution. In an RO system, the osmotic pressure of saline water is very significant because it can be used as a barometer to theoretically estimate the energy required for the separation of water molecules from saline water. Therefore, the osmotic pressure of any saline water should be determined to estimate the theoretical minimum energy required for the separation of freshwater from saline water.

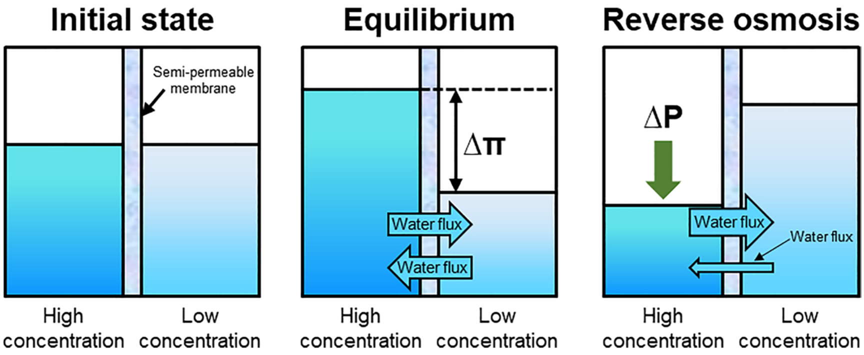

Figure 1.1 Schematic diagram of osmotic pressure and RO.

1.3 PRINCIPLE OF RO

The spontaneous water flux direction in the membrane system is from a highly concentrated solution to a low-concentration solution without any pressure applied to these solutions. As mentioned above, to reverse the spontaneous water flux direction, a hydraulic pressure higher than the osmotic pressure difference between the highly concentrated solution and the low-concentration solution should be supplied to the highly concentrated solution. This principle can be utilized to produce freshwater from saline water with a high-performance semi-permeable membrane, as shown in Figure 1.2, and this is usually called RO.

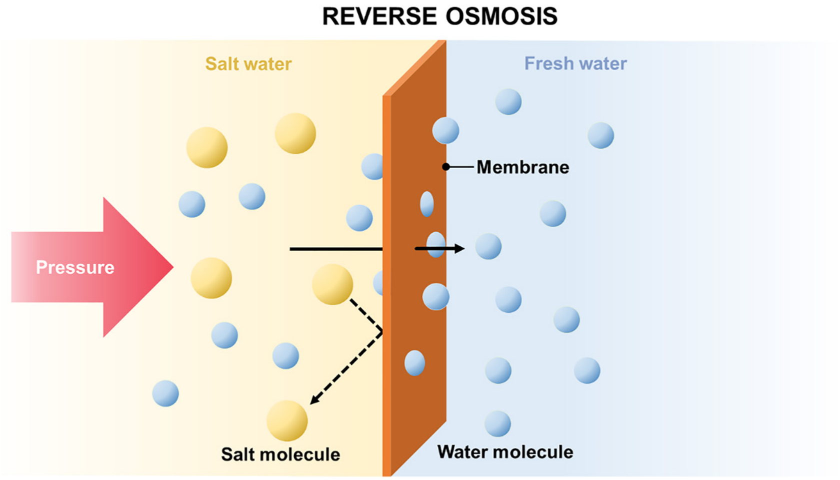

Figure 1.2 Freshwater permeation across the semi-permeable membrane in RO.

Many key terms utilized in RO are summarized in this chapter; it is recommended that readers familiarize themselves with these terms as they relate to current RO systems.

Recovery: Recovery is the ratio of the amount of water permeated through the RO to the amount of total water fed into the RO system. A high recovery indicates that the RO system can produce a larger amount of fresh water from the same amount of feed water. Because the feed water should be pre-treated to supply the RO system, a high-recovery RO system may be more economical. In addition, the capacity of the water produced from an RO system can be enhanced if the RO system is operated for higher recovery.

Permeate: The permeate denotes the water transferred through the RO membrane. The permeate is usually fresh water in an RO desalination system.

Rejection: Rejection is the ratio of the solution concentration of the permeate stream to the concentration of the feed stream. This is one of the main performance indicators of RO membranes. If the rejection is very high, the RO system can produce a very high-quality permeate with a very low salt concentration.

Retentate (concentrate): The retentate is water rejected from the RO membrane. The retentate consisted of salt and water retained in the RO system. Because the permeability of the semi-permeable membrane is much lower than that of water, the retentate has a higher concentration than the feed solution. The concentration and amount of the retentate stream are determined by the rejection of the RO membrane and the recovery of the RO system.