Reverse Osmosis Membranes for Desalination of Brackish Water

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Reverse osmosis (RO), which is commonly used for different water purification and desalination applications, is a remarkable process to separate dissolved inorganic and organic compounds from water. Over traditional methods of water treatment and purification, RO has many benefits such as production of high quality drinking water, simultaneous elimination of multiple pollutants, and simple operation procedure. As drinking water supplies are declining and demand for high quality water is increasing worldwide, RO membrane based water treatments will most probably continue to develop.

This research was aimed at better understanding the behavior of the thin film composite (TFC) polyamide membrane used in RO process under various operating conditions. The performance of RO membrane was evaluated in terms of salt rejection and water flux to simulate brackish water desalination process. The operating conditions included salt concentrations ranging from 2000 to 6000 ppm and operating pressure ranging from 100 to 250 psi. Based on experimental results, the performance of the TFC polyamide RO membrane was estimated at higher operating pressures (300-1000 psi). Based on mass transfer coefficient , solute transport parameter and water permeability that is characteristic of the membrane. In addition, the potential of using the TFC RO membrane to process water during oil and gas productions (with 1.5-2.5 % salt by weight), was demonstrated in this study. Besides simulation, experiments were conducted using real water as the feed solution.

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Dedication

This is dedicated to the one I love.

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Chapter 1

Introduction

1.1 Background

Scarcity of quality water is one of the most serious challenges our world is facing nowadays. Global water shortage areas have a population of 2,3 billion which is expected to grow to 3,5 billion by the year 2025. Studies revealed that millions of people suffer from water shortage, and 3900 children die every day because of using poor quality water which often contains disease causing germs and health hazardous pollutants [10] [11] [12]. Because of this dire situation, it is very important to provide clean, and fresh water with reliable resources to eliminate this problem. Seawater and other saline water sources, which comprises of a combined 95% of water on earth, are predicted to be a reliable source in the immediate future. There are two approaches have been developed to support sustainable freshwater production from the desalination of brackish and seawater: one based on thermal processes and the other based on membrane processes. With the help of existing water treatment technologies, both sources, sea and brackish water including rivers and reservoirs, can be used to produce fresh water reliably and constantly [11].

Thermal desalination technology is expected to gradually decrease because world fuel reserve is limited. Thermal desalination process also has major drawbacks such as inefficient burning of fossil fuel, incompetent use of heat energy, emission of greenhouse gases, corrosion of metals, high capital investment, and massive operational and maintenance costs [11]. In the light of this situation, desalination of brackish water by RO membranes has been proved to be a suitable solution for producing quality pure water. The technology has been successfully applied in various industrial water and wastewater treatment plants, agricultural irrigation and in remote areas where there is a lack of natural water [13] [14]

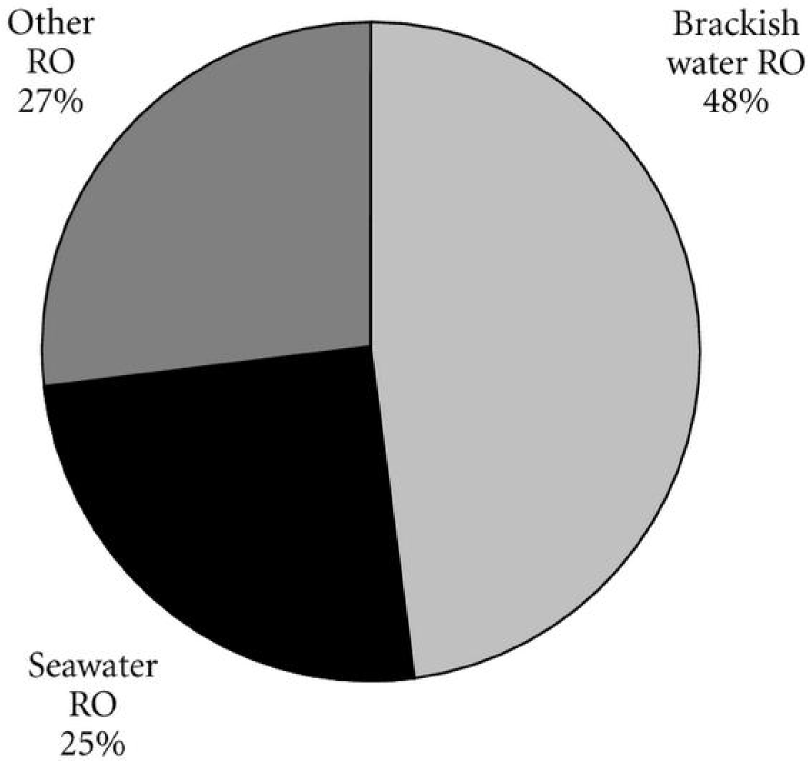

Figure 1.1: Percentage of RO desalination plant based on feed source of water in the world [1].

[15]. However, brackish water RO plants are less capable of producing freshwater than seawater RO plants. Nevertheless, if worldwide applications are taken into an account, the number of brackish water RO plants (48% of the total plants) is higher than that of seawater RO plants (25%) as illustrated in the Figure 1.1 [16] [1]. The remaining 27% of the RO plants are fed with wastewater and water from rivers [16].

Reverse Osmosis (RO) is the core of a membrane-based desalination process. The RO membrane can be defined as a permselective barrier between two homogeneous phases. Because of the concentration difference between two phases, water moves from one phase to another, and thereby, salts in water are separated. Recently, reverse osmosis processes have been an essential source for providing drinking water due to their lower costs and simplicity. Reverse osmosis membrane have been used extensively in desalination plants and particularly in remote areas. Early developments of the RO process had applied water pressure requirements of 120 bar to desalinate sea water. Recent developments have successfully reduced this pressure requirements to as low as 50 bar for desalinating sea water and 20 bars to desalinate brackish water using RO membrane technology [17].

The membrane performance can be experimentally determined in terms of two parameters: permeation water flux and solute rejection. These parameters play an important role in the membrane processes for desalination in an industrial scale. However, the typical use of RO process is limited by the operating conditions and energy cost according to types of feed water. For an example, desalination of sea water by RO process requires high operating pressures which consume more energy for treating sea water, while brackish water needs lower operating pressures. The type of feed water is important for designing the treatment plant including pretreatment steps, desalination method, and waste disposal. The salinity of the feed water is classified into three ranges: freshwater (0- 1500 ppm), brackish water (1500 to 10,000 ppm), and salinity water (10,000 - 45,000 ppm).The salinity of seawater is on an average of 34,000 ppm, whereas the salinity for brackish water is between 3000-10000 ppm. Water with salinity higher than 10,000 ppm is considered to be a high salinity water. Reverse osmosis treatment of seawater with a salinity range from 10,000 to 60,000 ppm, is thus a process for high salinity water treatment. On the contrary, the reverses osmosis treatment of brackish water with a salinity range from 1000 to 10,000 ppm, is a process for low salinity water treatment which is mainly done for plants fed by groundwater sources [17]. This thesis aims to investigate the impacts of operating conditions on membrane performance in order to improve the membrane productivity and selectivity. The membrane performance can decline according the fouling issues such as concentration polarization. As a results, the predication of membrane performance for desalinating brackish water can help to understand the impacts of different operating conditions in order to minimize the fouling issues by predicting the optimum operating conditions. Optimum operating conditions are very important to extend the membrane life and minimize the energy required for deliver a high efficient membrane performance.

1.2 Objectives

The objective of this research is to have a clear understanding of the thin film composite (TFC) polyamide flat sheet reverse osmosis membrane. The performance of RO membrane is evaluated by salt rejection and water flux at various operating conditions including operating pressure and feed salt concentration. The experiments were supposed to simulate a brackish water environment where sodium chloride is the primary salt component.

This study focuses on membrane desalination of brackish water by using commercial thin film composite (TFC) polyamide (PA) reverse osmosis (RO) membranes. The research consisted of the followings:

1. Investigating the reverse osmosis separation performance of TFC polyamide RO membrane for desalination of brackish water under different operating conditions such as feed sat concentration, and pressure.

2. Predicting the membrane performance for a wide range of operating pressures.

3. Carrying out a case study of desalinating high salinity water from an industrial site in Western Canada.

1.3 Thesis outline

This study includes a literature review on mass transport through RO membranes, salt rejection experiments in a laboratory scale RO process, and a discussion of the experimental results. The first chapter introduces the thesis work by showing background information about water accessibility and the importance of desalination followed by the thesis objectives and brief outline. The second chapter focuses on the engineering aspects of the reverse osmosis desalination process. It includes reviews of various desalination processes as well as the principle of reverses osmosis and the mass transport mechanisms discussed with comparing the two operating modes. Also, the membrane performance parameters are mentioned in this chapter. Next, chapter 3 presents the experiment setup and the procedure for membrane RO. The RO test station consisted of six cells. The performance of the membranes for water desalination was measured in terms of water flux and salt rejection under a cross flow mode. Chapter 4 demonstrates the results of the TFC RO membrane performance for desalination of brackish water. Also, the results of performance of the RO membrane at different NaCl salt conditions have been discussed considering the mass transfer coefficients and solute transport parameters, which were useful to predict the membrane performance at extended operating ranges. Moreover, this chapter includes the results of a carry out study implemented to evaluate the membrane performance for desalination of real brackish water in terms of permeate flux and solute rejection. The last section, chapter 5, describes the general conclusions. Based on the results revealed in this study, limitations of current work and recommendations for future studies are also provided in this final chapter.

Chapter 2

Literature Review

2.1 Desalination Technologies

Desalination processes can be classified into two main categories: thermal processes and membrane processes. Thermal desalination is one of the earliest methods used for treating seawater and brackish water by boiling water to extract steam (pure water) from brine to produce drinking water. It is mainly based on the evaporation and condensation process [18].The second group of desalination processes is membrane processes which use a selectively permeable membrane to permeate water while rejecting salt from the feed source.

The two most significant technologies in water treatment are commercially focused on the multi stage flash (MSF) and RO processes. These two processes are commonly used for desalination in the last two decades. In 2000 about 93% of the global seawater desalination capability comprised 11.6 million (m^3/day) and 11.4 million (m^3/day) of water purification from MSF and RO plants, respectively [9]. However, the reliance on RO seawater desalination has steadily increased due to its lower costs and easier operating procedure. This leads to the production of 65.5 million (m^3/day) of reverse osmosis desalinated water, representing 69% of the desalinated water capacity [9].

The different desalination classifications are illustrated in Figure 2.1 [2]. Existing industrial desalination processes are dominated by two main categories, thermal desalination technologies such as multi-stage flash distillation and multi-effect distillation, and desalination by membrane technologies, which includes reverse osmosis. These will be described in detail in the following section.

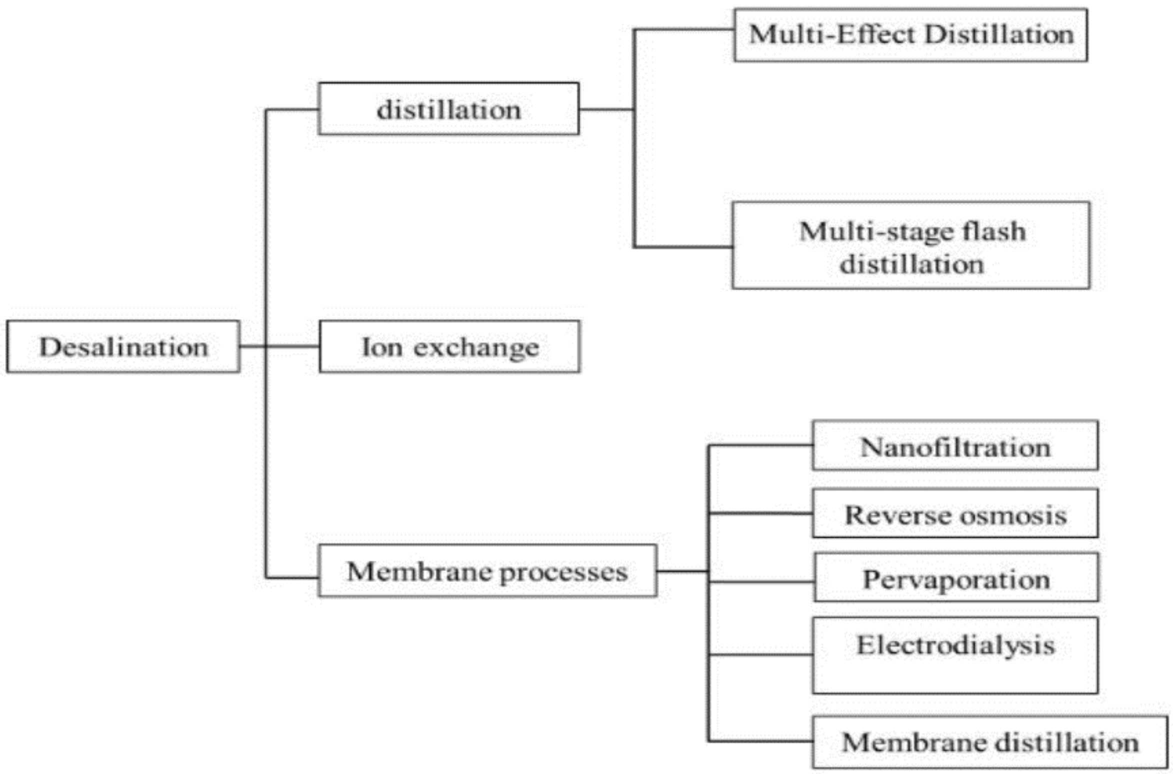

Figure 2.1: Classification of water desalination technology process [2].

2.1.1 Thermal Desalination Technologies

Thermal desalination is a practical solution for producing freshwater by treating saltwater and brackish water thermally [19]. The process is based on heading feed saline water to evaporate continuously at lower pressures by reducing the boiling point to reduce the required heat energy in many successive vessels. At the inlet of the vessel, a fraction of pressurized feed water flashes into steam to split the vapor from salt. Pure water goes up to be conducted and the salt is dropped down. The most common thermal desalination processes are:

1-Multi-effect distillation (MED)

The MED process has been used for seawater desalination in the last 5 decades [3]. MED process acts as a heat exchanger between steam and seawater or brine that takes place in a series of stages. Lower pressures and temperatures are used to reduce the boiling points in every stage, as shown in Figure 2.2 [3].

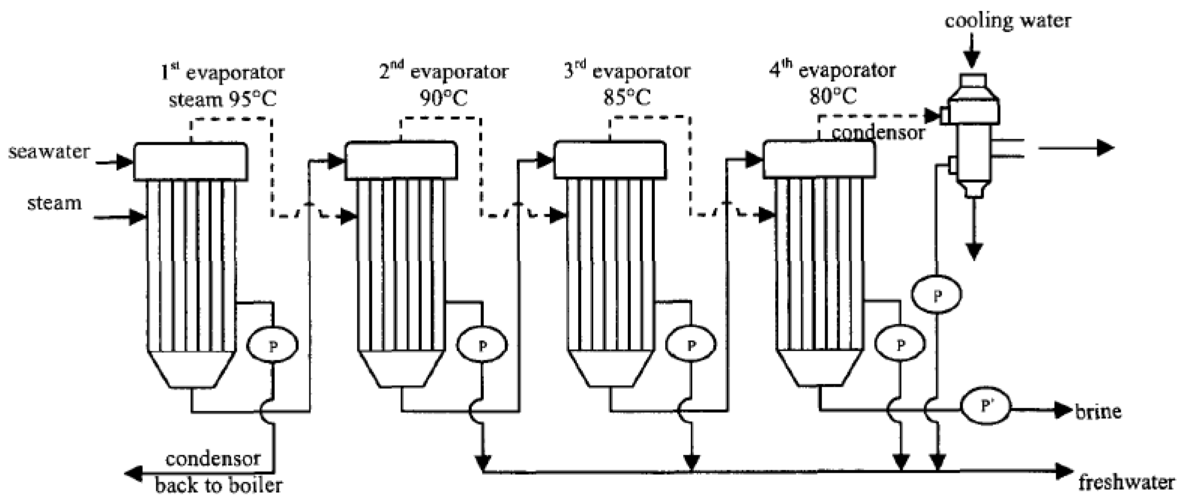

Figure 2.2: MED process flow diagram [3].

In the first effect, the seawater is scattered onto the evaporator tube, which is preheated by steam. The steam is condensed while the seawater is evaporated to separate pure water from salt. The evaporated water steam of the first effect is used as steam for the second effect, while the condensed steam is recycled to the boiler. In the second effect, the feed is the brine solution of the first effect. The same process will operate at slightly lower temperature and pressure. The heat transfer rate of MED process is achieved because of the thin film boiling and condensing conditions [20].

MED process has been engineered in two designs, horizontal and vertical mode. In the horizontal mode, the feed water is scattered on the outside surface of the tubes. Steam flows through the tubes to evaporate the feed water, resulting in the steam to condensate inside the tubes. Spray nozzles help to distribute the feed water uniformly over the heat transfer tubes. The vertical design is the opposite of the horizontal design, the feed water flows through tubes, while steam is sprayed on the top of the outside tube surface. The water production is usually very high in MED related to steam consumption, which is more efficient than MSF for energy waste. However, scaling deposition of calcium sulfate is the main reasons for fouling to occur in MED at high operating temperatures. Consequently, fouling has a major effect on the effective contact surface and heat transfer between brine and steam inside the heat exchangers. As a result, the operating condition is limited to a high temperature of feed controlled below 120 °C, which is the highest top brine temperature (TBT) to avoid any deposition scaling of calcium sulfate. The lowest acceptable temperature at the bottom condenser is designed to be the temperature of seawater fed in the process and is considered as cooling water [3]. Also, the number of effects is designed based on the feed temperature and the difference in temperature between the effects. The typical design is required to have 5 °C deference in each effect. Therefore, according to the production rate, feed temperature and temperature variation between each effect, a MED plant can vary from 8 to 16 effects [3].

2-Multi-stage flash distillation (MSF)

Since the early 1960s, MSF process has been known as the most practical process for seawater desalination [19]. MSF process has the same principle as in MED process. It is a thermal process where it needs high amount of heat to evaporate feed water, followed by condensation of vaporized steam as product (distillate) water. MSF process consists of a series of stages. Each stage has a heat exchanger to condense the steam and to preheat seawater before entering a stage and a condensate collector to collect the water after condensation. At each stage, the brine steam is flashing at the inlet stage to separate the vapor water from saltwater, where the demister is used to collect the brine water that comes with flashed off vapor. Condensate water is collected as product, and the brine water is discharged as by-product, while a portion of it is recycled for heat recovery. The process is repeated at each stage with a lower pressure and temperature at a lower boiling point, as shown in Figure 2.3 [4].

The MSF process has many advantages over MED process due to reliability and simplicity of the process, which can be explained below in three points:

1. Less corrosion risk can affect the performance efficiency of heat transfer rate because steam formation occurs within the bulk liquid in a place of the hot tube surface, where as in MED process, steam forms during heat exchange process with saline feed water.

2. Fouling can be easily controlled by regulating the maximum top brine temperature (TBT) under 110 °C to avoid the risk of corrosion. Adding anti-scalants helps avoiding the risk of organic precipitation [21].

3. Less effect of feed water concentration variation or impurities as the process can produce product water with 50 ppm of total dissolve solid [21].

The main drawback of MSF process is the higher reduction in the production performance ratio compared to the higher energy consumption for evaporating water. Apparently, the MSF process is considered to be more expensive than MED [20]. However, MSF

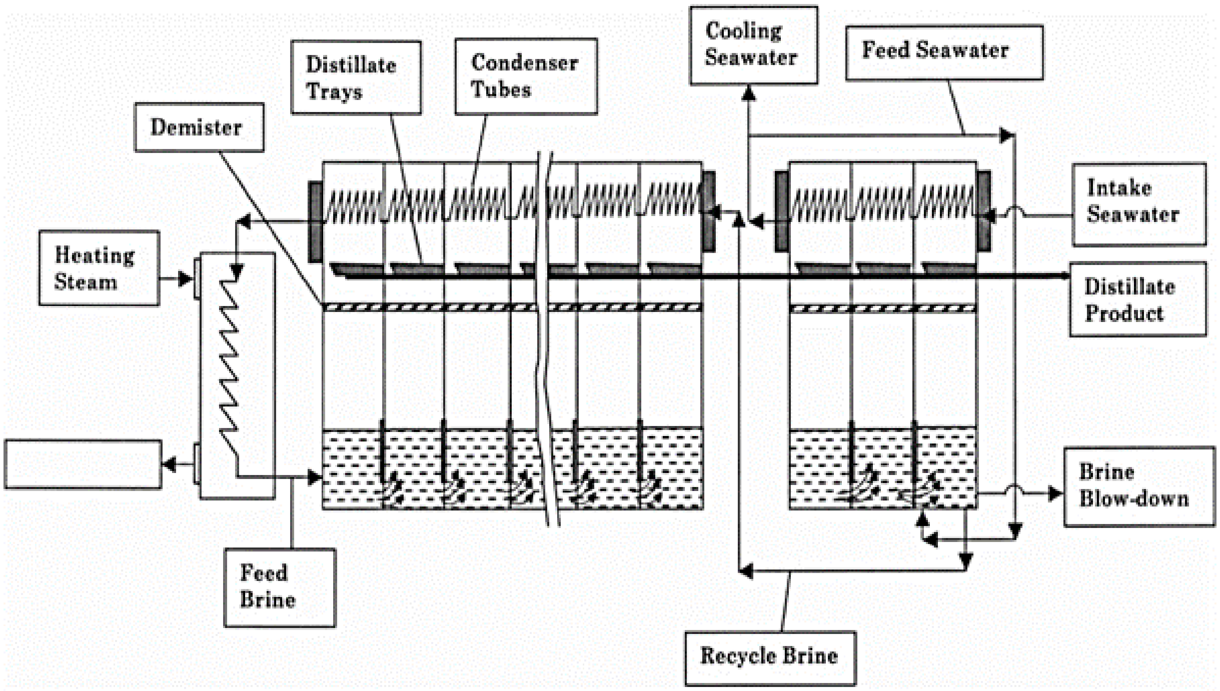

Figure 2.3: MSF process flow diagram [4].

process is still claimed to be an important practical process for sea water desalination, especially for a high production rate [4].

2.2 Membrane Technologies

A membrane is a thin barrier that prevents dissolved ions to transport with water. The membrane is mostly fabricated from polymer materials such as polyamide and cellulose acetate. Membrane processes can be classified for comparison based on various characteristics:

1. Membranes can be classified based on morphology or structure, such as symmetric and asymmetric membranes.
2. Driving force is one of the most important membrane classifications that includes four different kinds of driving forces:

(a) Pressure-driven processes such as reverse osmosis, nano-filtration, ultra-filtration and micro-filtration are classified according to the applicable different range size species that are designed to remove by the membrane, as shown in Table 2.1. [17].

(b) Concentration gradient-driven processes such as reverse osmosis, pervaporation and dialysis.

(c) Temperature gradient-driven processes such as membrane distillation.

(d) Electrical potential-driven processes such as electrolysis.

3. Separation mechanism models used for describing the transport process within the membrane such as mechanistic approaches and phenomenological approaches.

Table 2.1: Classification of pressure driven membrane separation processes[9].

Membrane process	Size cut-off range (μm)	Examples of materials separated
Microfiltration (MF)	0.05-1.5	microbial cells, large colloids, small particles
Ultrafiltration (UF)	0.002-0.05	macromolecules, viruses, colloids
Nanofiltration (NF)	0.0005-0.007	viruses, humic acids, organic molecules, Ca^{2+}, Mg^{2+}
Reverse osmosis (RO)	0.0001-0.003	aqueous salts, metal ions

As shown in Table 2.1[9], every process operates at a different particle size range. For example, reverse osmosis and some of the nanofiltration processes can be used for water desalination applications by retaining salts and other minerals with a particle size range 0.0001 to 0.003 μm for RO and 0.005 to 0.007 μm for nanofiltration. However, microfiltration and ultrafiltration have to use in larger particles size ranges 0.05 to 0.15 μm and 0.002 to 0.05 μm, respectively [9]. However, the separation mechanism is one of the main differences between the reverse osmosis process and other filtration processes. In the filtration process, the separation operates as a sieving mechanism that has physical separation of particles according to membrane pores which allow smaller particles to pass and reject the particles larger than the pore range of the filter. On the other hand, the separation with the membrane is based on a diffusing mechanism that allows water to diffuse through the pores of the membrane, and the salt is rejected by the membrane, thereby generating high purity water on the permeate side.

The membrane separation can be used for different applications. The membrane technology, specifically RO membrane, is a competitive choice for water desalinating compared with other processes such as MSF and MED processes, especially in remote locations and with moderate capacity. RO process has many advantages that allow it to be preferable process for water desalinating. First, most membrane separation processes do not need any phase change and chemical additives for separation. Rather, they depend on physical separation only. Moreover, they do not require heat for separation, so RO separation process is economically and energetically favorable over thermal distillation for water desalination. Additionally, they are flexible to meet the industrial requirements for improvements in production or reducing the equipment-size at a high production capacity [22].

2.3 Basic Principle of Reverse Osmosis

The principle of osmosis describes that when a semipermeable membrane divides two saline solutions with different concentrations, water spontaneously flows from the lower salt concentration solution side to the higher salt concentration solution side. The membrane will allow water to permeate, but it will reject salt to permeate with the water. The transport of water through the membrane continues until the chemical potential of water reaches the equilibrium state at both sides and then the osmotic pressures are balanced. At this stage, the water flow across the membrane stops when both sides have the same salt concentration. The equilibrium in the chemical potential is the main factor to balance both sides of the solution and stopping the flow of water within the membrane. However, the chemical potential can be changed if the salt concentration is changed by, for example adding salt. As a result, the chemical potential of the salty side becomes low, whereas the side of less salt or pure water has a higher chemical potential. This difference allows water to transport from the pure water side (higher potential) through the membrane to the salty water side (lower water potential). The transport continues until the difference of the chemical potential between the two sides of the membrane balances. Osmotic pressure is a form of driving force that forces pure water to flow from the diluted side to the concentrated side.

Reverse osmosis is the opposite process of natural osmosis process. It is used to separate the salt water by applying an external pressure, that is higher than osmotic pressure, to force the water flow from the concentrated side (salt water) through the membrane to the diluted side (pure or low salinity water). The applied pressure, which is greater than the osmotic pressure, is a function of salt concentration and temperature. Osmosis and reverse osmosis processes are schematically presented in Figure 2.4.

When a saline solution is added to one side of a semipermeable membrane and other

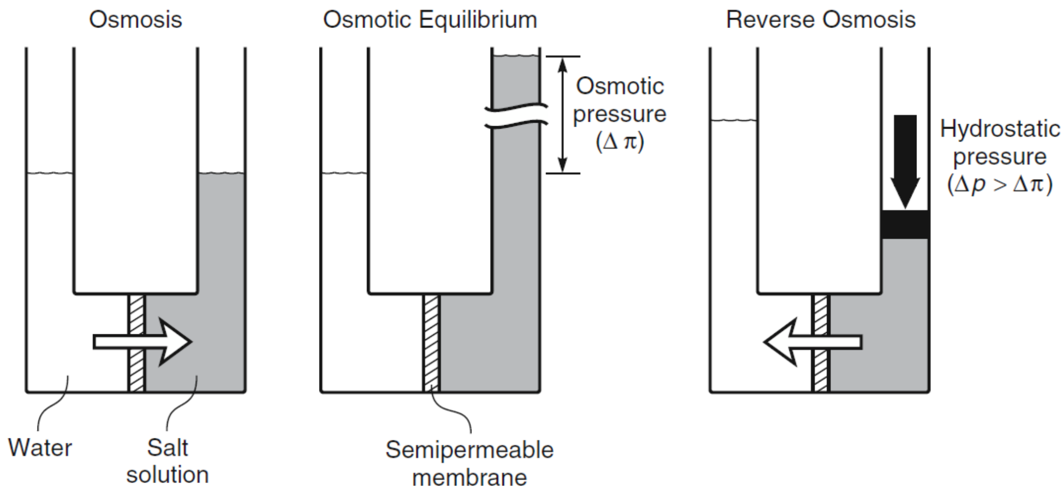

Figure 2.4: Principle of reverse osmosis [5].

side has a lower salt concentration or pure water, water spontaneously will flow from the lower salt concentration side to the higher salt concentration side until chemical potentials of water at both sides balanced. If the external pressure is applied to the salt solution side, the movement of the fresh water to salt water is reduced until the applied pressure is equal to the osmotic pressure, which reaches osmotic equilibrium. At the equilibrium state, there is no water flow between the two sides of the membrane. However, when the external applied pressure becomes higher than the osmotic pressure on the salt solution side, water starts to flow in opposite direction, that, from the concentrated side (salt water) through a semipermeable membrane to the diluted side (pure or low salinity water). In many industrial practices, very high external pressure is often used for desalination of highly concentrated salt solution (such as seawater) that has high osmotic pressure to reverse the natural osmotic process to produce pure water. This is known as reverse osmosis.

2.4 Transport Models for Reverse Osmosis (RO) Membrane

There is a strong need for describing the transport process within the membrane clearly. The performance of RO for water desalination can be predicted by using a model to describe mass transport in RO membranes with help of experimental data at different operating conditions. The separation efficiency of RO membrane and the permeate flux are the key parameters that can be experimentally obtained at different operation conditions. The model uses the experimental data to calculate the fundamental transport coefficients characterizing the membrane performance.

There are basically two approaches to modeling [23]. The first is based on phenomenological relationships that depict the membrane as a black box and characterize the process of separation based on irreversible thermodynamic fundamentals. According to this model, due to the relatively slow membrane permeation, the system can be supposed to occur near equilibrium. However, the major drawback of this approach is that it does not focus on providing any additional information about the transport mechanism of the membrane to predict how the structure of the membrane affects the transport process within the membrane[23]. In contrast, the second approach is based on mechanistic models such as the solution-diffusion model for dense membranes and preferential sorption capillary flow model for porous membranes. The mechanistic approach illustrates how the separation will occur throughout the membrane. All models of mechanistic approaches seek to interface separation with the structure-related parameters of the membrane. This study will use both solution diffusion model and perforation sorption capillary flow model for predicting mass transfer in reverse osmosis membranes. This approach offers reasonably simple physio-chemical understanding of the membrane transport.

2.4.1 Solution Diffusion Model

The Solution diffusion model was proposed initially by Lonsdale in 1965, assuming that the membrane is dense and the solvent and the solute transport according to the diffusion mechanism by the effect of concentration gradients [24]. According to this model, the key parameters that can be used to characterize the membrane performance are the solvent and solute ability to dissolve and diffuse in the membrane which determines the permeability of the membrane. Solvent flux is governed by the magnitude of the difference between applied pressure and differential osmotic pressure between the solutions on both sides of the membrane, while the solute flux is governed by the salt concentration difference between the feed and the permeate [25].

2.4.2 The Preferential Sorption Capillary Flow Model

Kimura and Sourirajan proposed the preferential sorption capillary flow model initially in 1970 [26][27]. There were many assumptions used for predicating the mass transport in the membrane. First, the membrane surface is microporous and mass transport occurs only through the pores in the membrane skin layer. This means the solute separation is determined by the surface structure and amount of pressurized feed transport within membrane capillary pores. For example, when external pressure is applied to the concentrate of the solution side of the membrane, both solvent and solute will be forced to permeate through the micropores of the membrane. However, the solute is rejected because of preferential adsorption of solvent which allows water to adsorb into the layer pores. The preferential adsorption of solvent is mainly due to the physio-chemical nature and pore size of the surface layer. The schematic of mass transport in Figure 2.5 showing the development of concentration profile within the membrane and the concentration polarization effects as the concentration feed solution c_{A1} is increased and it reaches the membrane surface. As a result, the diffusion through the membrane occurs due to the concentration at boundary layer c_{A2} to produce permeate solution with higher than expected permeated concentration c_{A3}.

For a precise prediction of the membrane performance, a clear impact of concentration polarization is needed to be considered for calculating and describing the mass transport of solute and solvent through the membrane. As a result, many studies tried to investigate the impact concentration polarization film layer by determining the mass transfer coefficient, which is related to the thickness of film layer of concentration polarization [28] [29]. Whereas, some research tries to estimate mass transfer coefficients theoretically[30].

The general description of solute and solvent transport equations is according to the irreversible thermodynamics approach. However, the following equations are set by Kimura and Sourirajan approach that describe the fluxes of both solvent and solute that include the effect of the concentration development profiles within the membrane as represented in Figure 2.5 to introduce the solvent and solute flux by Equations 2.1 and 2.2 shown below.

$$J_B = A\,(\Delta P - \Delta\pi) \tag{2.1}$$

$$J_A = \left(\frac{D_{Am}K_A}{\delta}\right)(c_{A2} - c_{A3}) \tag{2.2}$$

Where J_B is the product water flux ($kmol/m^2s$), A is the pure water permeability constant ($kmol/m^2s - kPa$), P is the operating pressure (KPa), $\Delta\ \pi$ is the difference in the osmotic pressure across the membrane (KPa), J_A is the flux of solute permeation membrane, D_{Am} is solute diffusivity coefficient of membrane, δ is effective thickness (m), K_A is distribution constant relating the concentrations of solute inside the membrane and the liquid phase. $(D_{Am}K_A/\delta)$ is the solute transport parameter (m/s), and C_{A2} and C_{A3}

are solute concentration on membrane surface of the feed side and permeate in (mol/m^3) as illustrated in Figure 2.5.

Mass transfer coefficient, k, the solute transport parameter $(D_{Am}K_A/\delta)$ and A, which is the pure water permeability constant, are used for predicting the performance of membrane separation and productivity at different operating conditions [27]. Experimentally, pure water permeability constant, A, can be calculated for any membrane by using Equation 2.1 to test the solvent permeability performance of the membrane. Also, the solute transport parameter $(D_{Am}K_A/\delta)$ can be found at different operating conditions according to the Kimura and Sourirajan model [27], and the details can be found in reference [6]. The following equations are used for calculating the solute transport parameter $(D_{Am}K_A/\delta)$ the pure water permeability, A.

$$A = \frac{J_B}{\Delta P} \tag{2.3}$$

$$\left(\frac{D_{Am}K_A}{\delta}\right) = \frac{J_B}{(c)\,(\frac{(1-X_{A3})}{X_{A3}})(X_{A2} - X_{A3})} \tag{2.4}$$

Where it is assumed that c1=c2=c3=c, which represents total(solute and solvent) molar concentration (solute and solvent) (mol/m^3) , X_{A2} and X_{A3} are the solute and mole fractions on layer of low and high side of membrane, respectively.

Mass transfer coefficients, k, is important for predicting the behaviour of a given salt through a desalination membrane. It is illustrating how much mass can transport through the membrane at a given time. In other words, it helps illustrate solvent and solute flux that flows within the membrane. However, as shown in Figure 2.5, there is a boundary layer due to salt accumulation near the membrane surface, resulting in an increasing concentration of salt and osmotic pressure. As a result, there will be a back diffusion of solute, which affects the mass transfer coefficient, k [31] [6]. The Kimura-Sourirajan Analysis uses boundary film theory which assumes there is a concentration polarization layer to help describe mass transfer coefficient, k, by following Equations 2.5, 2.6, 2.7, 2.8, and 2.9, which used to find the mass transfer coefficient, k, using Equation 2.10 [6][27].

$$exp\left(\frac{v}{k}\right) = \frac{(c_{A2} - c_{A3})}{(c_{A1} - c_{A3})} \tag{2.5}$$

where

$$c_{A1} = c_1 \, X_{A1} \tag{2.6}$$

$$c_{A2} = c_2 \, X_{A2} \tag{2.7}$$

$$c_{A3} = c_3 \, X_{A3} \tag{2.8}$$

and also

$$v = \frac{J_A + J_B}{c_1} \tag{2.9}$$

Where, equation 2.5 represents the effect of concentration polarization and can be used to find the boundary concentration c_{A2} (mol/m^3). Experimentally, velocity of solution v (m/s) can used for predicting mass transfer coefficients k (m/s) when feed and permeate molar concentration assumed to be constant ($c_{A1} = c_{A2} = c_{A3} = c$). From above equations, the following equation for mass transfer coefficient can be obtained by Equation 2.10 [6] [27]:

$$k = \frac{J_B}{(c)\,(1 - X_{A3}) ln(\frac{(X_{A2} - X_{A3})}{(X_{A1} - X_{A3})})} \tag{2.10}$$

The membrane performance can be predicated using the basic parameters that illustrate the effect of the separation efficiency and permeation flux of RO membrane at different operating conditions.

2.5 Experimental Evaluation of Membrane Performance

In RO separation, there are two parameters that can be evaluated experimentally. Permeability and separation efficiency of the membrane. The membrane permeability can be measured in terms of permeate flux, which represents the amount of permeate through a given effective membrane area. Equation 2.11 is used to calculate permeate flux.

$$J_B = \frac{V}{t\,S} \tag{2.11}$$

Where, V is the permeate volume obtained during a specific time, t, through the effective membrane area, S. The permeation flux depends on many factors such as the intrinsic permeability and the membrane thickness. Therefore, TFC RO membranes are used in this experiment to reduce the membrane thickness and to improve the membrane productivity. The separation efficiency of RO for water desalination can be represented by the amount of salt rejected within the membrane, as described by Equation 2.12.

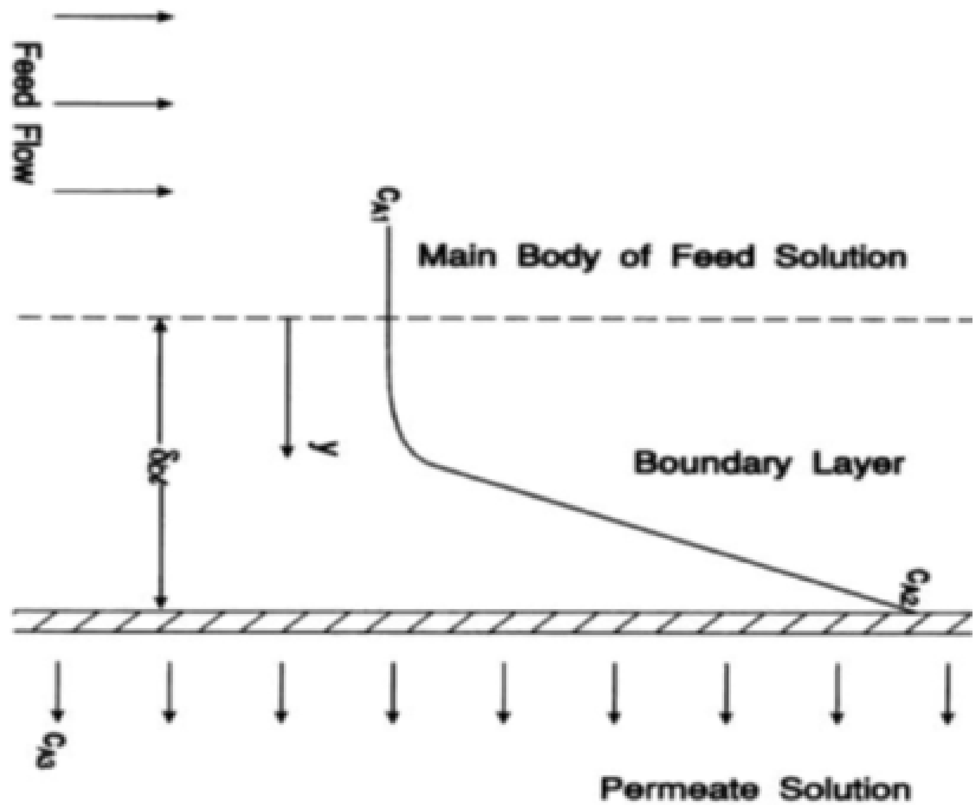

Figure 2.5: Illustration of concentration polarization effect in RO membrane transport process [6].

$$R = \left(1 - \frac{c_{A3}}{c_{A1}}\right) 100\% \tag{2.12}$$

Where, R is the percentage of salt rejection salt concentrations. c_{A3} and c_{A1} are measured by conductivity meter to indicate the amount of salt present in the permeate and feed solutions, respectively. These two parameters are important factors to examine the performance of any type of membrane or configuration at steady state conditions for different operating conditions such as operating pressure and feed concentration.

2.6 Reverse Osmosis Membranes Modules

The module is a group of membranes packaged for practical applications. Membrane modules are designed in different shapes and ways for improving membrane performance and reducing the fouling issues. The treatment of water by RO membrane process can be packed mainly in three different designs including flat sheets, spiral, and hollow fibers modules. Besides, the membrane may be operated in different modes including cross-flow and dead-end mode. In this thesis, a flat sheet membrane in cross flow mode was mainly used in the experiments, except for a case study of desalinating an industrial water from Western Canada where a spiral membrane module was also used.

2.6.1 Membrane Modules

In assembling reverse osmosis membranes, the following strategic design layouts are mainly used:

1. Flat sheet module

   It is a very useful design for small scale such as laboratory scale experimental research work. It has many advantages for use such as simplicity to fabricate and easy to clean and replace. Also, it is a cheaper alternative that is used for low capacity with a small membrane area which saves the quantity amount of chemicals and materials. However, it has a low packing density that needs to have supporting layers to prevent any damage to the membrane surface. More details of the process and components will be described in chapter 3.

2. Spiral wound module.

   Practically, the spiral wound system is one of the most commonly used in water treatment membrane process due to acceptable water permeability rate and low fouling impacts. The spiral wound system consists of two sheets of membranes, placed in parallel and sealed with glue at three sides to form a membrane envelope. These membrane envelopes are separated by placing a porous spacer between the membranes for providing space for permeate transport and exit through the open end of the membrane envelope. Also, the feed spacer is used for giving space and authorizing the feed solution to transport within the membranes by placing it between membrane envelopes that are rolled around a collecting pipe in a spiral shape. The membrane is then packed in a cylindrical vessel for use under high pressure so that the feed, passes through module inlet feed and the permeate stream and brine are collected via the two outlets of the spiral wound membrane module.

3. Hollow fiber module.

   Hollow fiber module is a configuration that has the highest packing density, which is as high as 30,000 m^2/m^3 [32]. Hollow fibers are thin tubular membranes, and a hollow fiber module is comprised of thousands of hollow fibers bundled and sealed together on both ends in a pressurized vessel. Fibres are self-supporting which can stand for higher pressures externally than internally, so shell-side feed layout is often preferred for hollow fiber membrane modules. The Hollow fiber membrane module is preferably operated in the outside-in mode with selective skin layers of the membrane on both sides of the fibers. A perforated central pipe is located in the center of the module through which the feed solution enters. In another design, the hollow fibers may be arranged in a loop and are potted on one end, the permeate side.

2.6.2 Membrane Modes

The RO membrane process operates in two different flow modes or configurations: dead-end and cross-flow configurations. In dead-end mode, the feed flows in a perpendicular direction to enter the membrane and flows along the membrane surface, and only one stream discharges from the membrane module. In the cross-flow mode, the feed flows tangentially to the membrane surface, and there are two outlets for solution discharge from the membrane module for the permeate and brine, as illustrated in Figure 2.6 [7].

In most applications, the horizontal flow direction in the cross-flow mode can drag the accumulated salt rejected by the membrane to avoid formation concentration polarization and fouling at the membrane's surface. However, the dead-end operation mode limits the permeate flux because the vertical flow causes pore blocking and cake layer formation on the membrane surface which needs a back-washing technique to limit the formation of the salt in the membrane surface. As a result, for the water treatment process, cross-flow operation is more practical than dead-end operation mode to avoid concatenation polarization fouling and reduction in permeate flux.

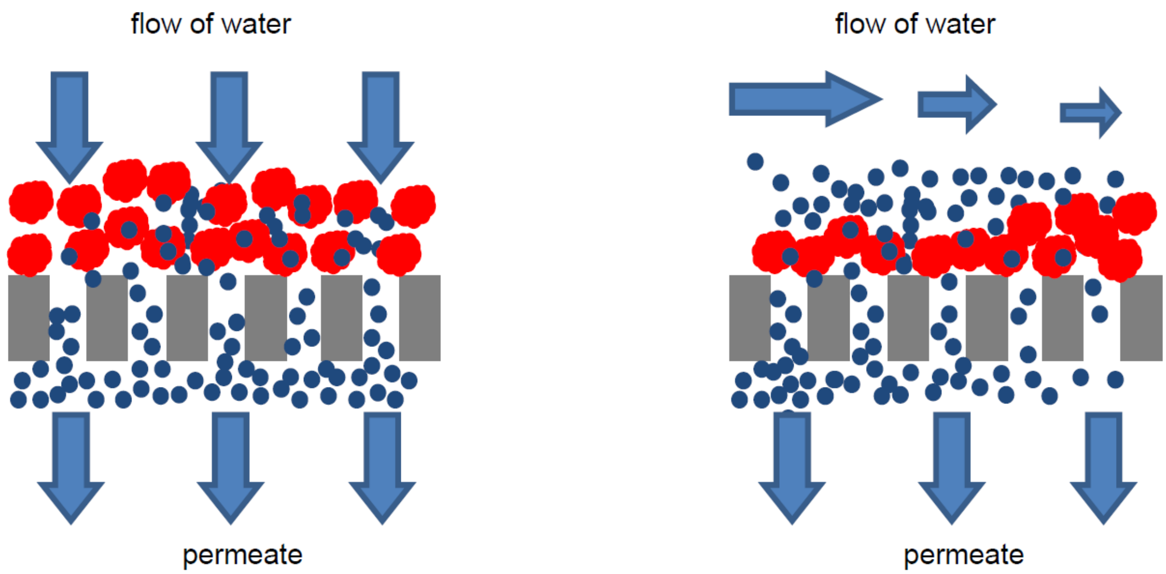

Figure 2.6: The schematic of dead-end mode (left) and the cross-flow mode (Right)[7].

Chapter 3

Methodology and Experiment

3.1 Experimental Apparatus

The experimental set up system is a continuous cross-flow apparatus with six membrane units set in parallel to measure the permeate samples under identical feed conditions. Figures 3.1, and 3.2 show the various components of the experimental set up RO system. The RO membranes are all thin film composite polyamide (TFC PA) in flat sheets that simulate spiral RO membrane elements used commercially. The experiment was designed to simulate brackish water environment and sodium chloride was used as solute. The RO apparatus was run as a continuous process that used cross-flow mode to avoid membrane fouling.

The RO system consists of five major components:

1. Feed Tank (25 L)
2. Pump
3. membrane cells
4. Pressure Gauges
5. Control valve

Figures 3.1, 3.2, and 3.3 show the whole experimental layout of the membrane cross-flow unit system. The feed solution was pressurized from the feed tank through a feed pump

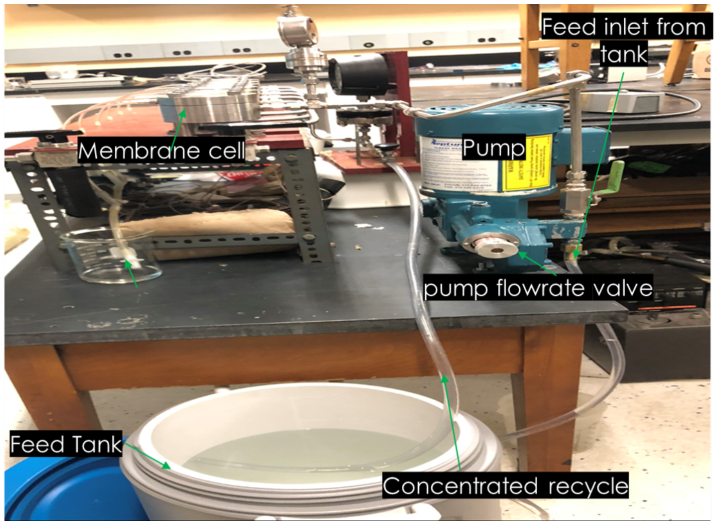

Figure 3.1: Overall membrane unit set-up design.

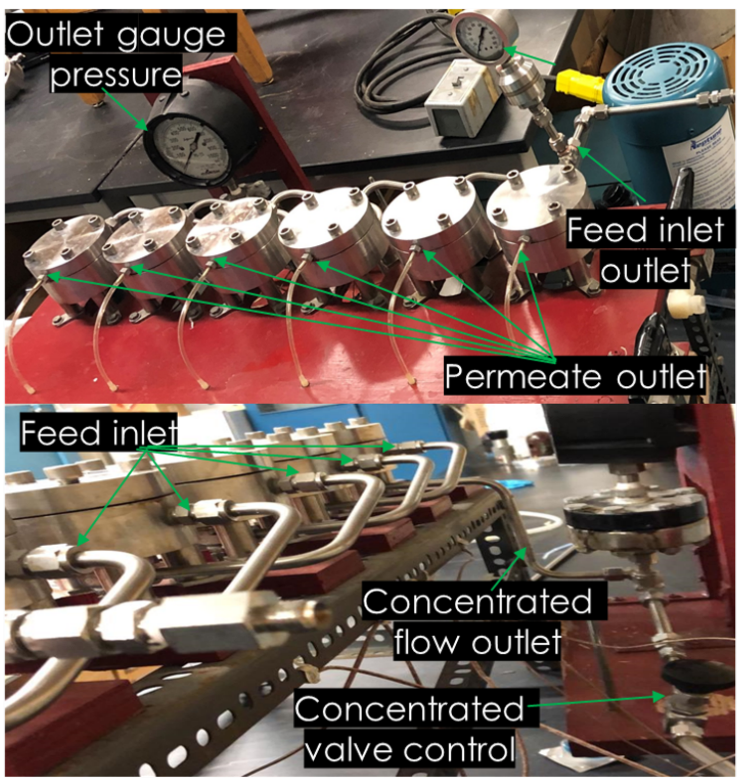

Figure 3.2: Front and back view of experimental set-up.

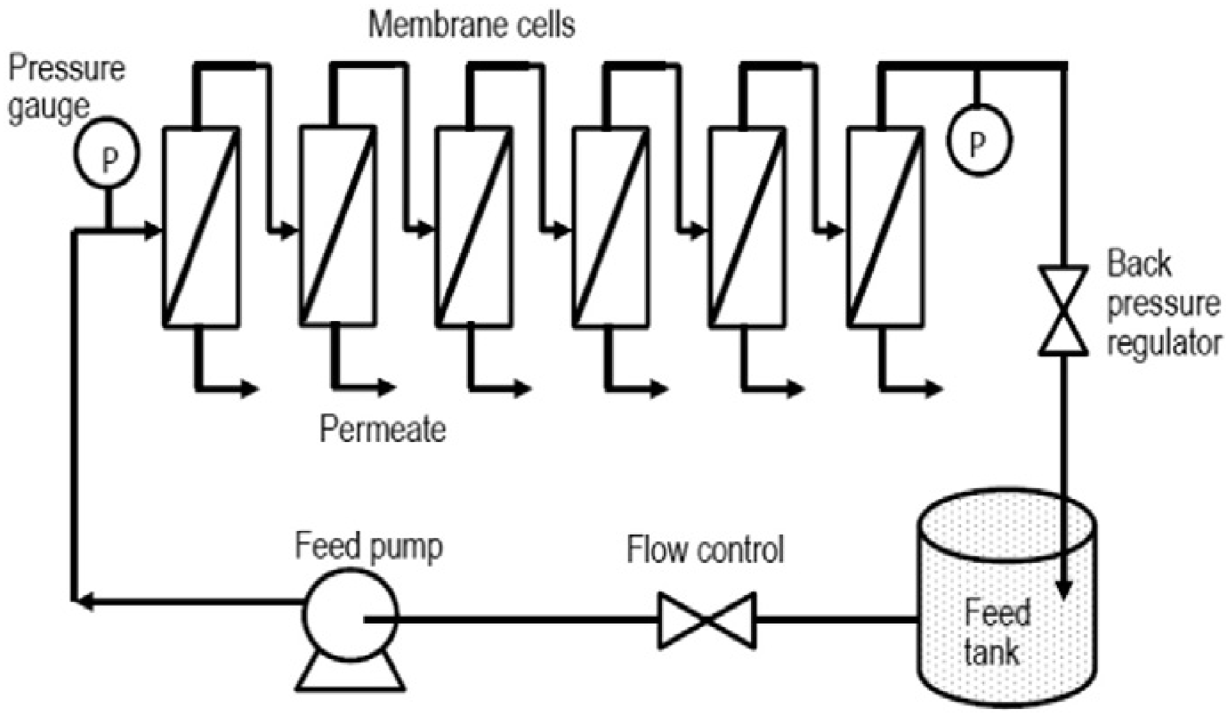

Figure 3.3: Layout design of the membrane cross-flow unit system [8].

with stainless steel tubing (Model NO. : 525 E-N3, Neptune Chemical Pump Company, Inc.) to the inlet of the RO unit. Unless described otherwise, the feed flow rate was set at 1.35 mL/sec by manipulating the pump flow valve at the outlet. The feed solution entered the first membrane cell, and then flowed through subsequent cells that had an active surface 14.75 cm^2 for water desalination by rejecting salt using the TFC PA RO flat sheet membrane. The permeate product (water) was discharged from the permeate outlet of each cell while the feed solution passed to the next cell. The concentrated salt solution exited through the concentrated outlet.

During experiments, flow rates of the permeate and brine solution were measured manually by collecting the solution in a measuring cylinder over a specific time with help of a stopwatch. Besides, the concentrations of feed and permeate were measured by using an Orion 162A conductivity meter. During the experiment run, operating pressure was manipulated by adjusting the control outlet valve to maintain a constant operating pressure. For this purpose, a pressure gauge was placed at the exit of the recycled brine pipe. The experiments were run in a continuous mode, where the brine was recycled to the feed tank directly after it was discharged from the membrane. The permeate samples were mixed after their flow rates and concentrations were measured and recorded. This way, a constant feed concentration was maintained by mixing and recycling the brine and permeate samples to the feed tank. Also, the temperature of the feed solution was kept at the room temperature of 25 °C. It may be mentioned that the feed flow rate was much higher than the permeate flow rate, and thus, the variation in salt concentration in the feed solution was negligible. This allowed us to determine the membrane properties at given feed concentrations.

In evaluation of membrane performance for processing produced water from an oil production site in Western Canada that contained a high level of sodium chloride, small spiral modules were used as well. The test protocol was the same except that the "real" water was per-filtrated prior to RO treatment. Details of the case study will be presented in Section 4.4.

3.2 Preparation of Simulated Brackish Water

Sodium chloride was used to prepare simulated brackish water. Table 3.1 shows the different feed concentrations in part per million (ppm) and the respective mass of NaCl in grams per liter of water (g/L) used in the study.

Table 3.1: Feed solutions.

Solution No.	Concentration (ppm)	Mass of NaCl (g/L)
1	0	0
2	2000	2
3	4000	4
4	6000	6

The following steps are the procedures of calibrating and preparing the feed solutions.

1. Conductivity meter in Figure 3.4 was used to measure the feed solution of known concentration. The feed solutions were used also used as standard salt solutions for calibrations.

2. As seen in Table 3.1, using weight balance and volumetric flasks, four experimental feed solutions were made by adding known amount of NaCl to distilled water.

3. At each run, amount of NaCl was measured in the samples of both permeate and feed solutions. The Volume of the permeate solution samples were measured every 2 hr, which was used to calculate the permeate flux according to Equation 2.11.

4. All steps described above were repeated for every feed solution at all operating pressures in order to calculate the salt rejection and permeate flux.

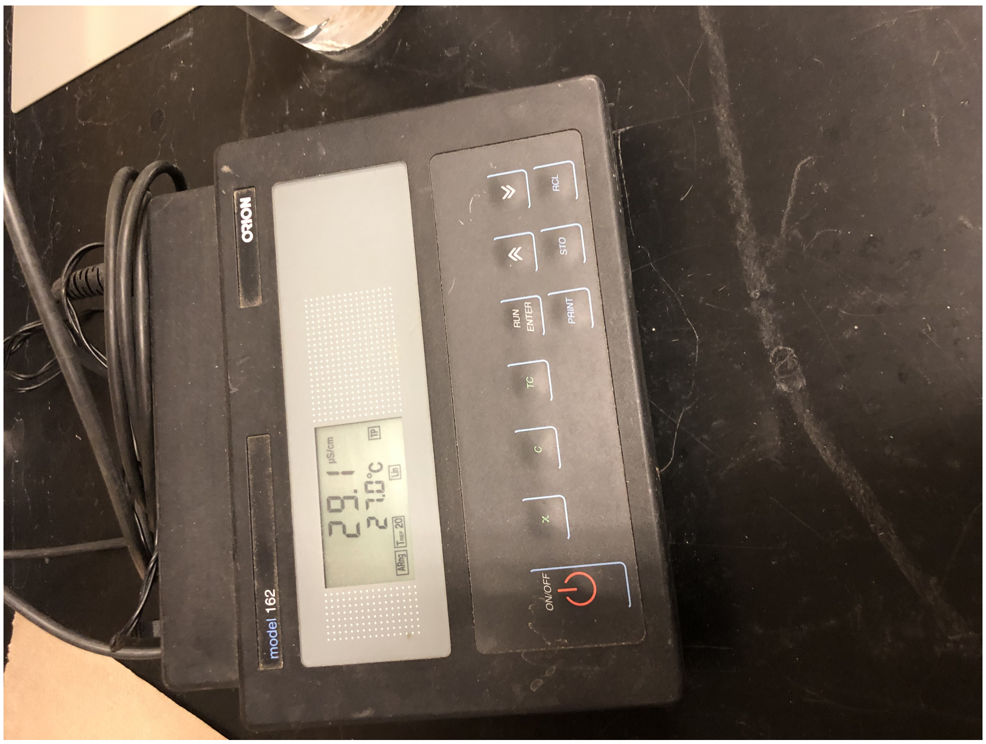

Figure 3.4: Experimental conductivity meter.

3.3 Experimental Procedure

Experimental procedures of brackish water treatment by the RO membrane are shown below.

1. Before running the experiments, the feed tank was filled with de-ionized water. Then the pump was switched "ON" mode to start pumping de-ionized water to the membrane unit for 6 h in order to wash and pre-condition the membrane unit.

2. The membrane system was checked for leaks and the stability of feed flow at different operating pressure was examined as the test was running.
3. When the system became stable, the RO experiment was started, and permeate flux of pure water at different operating pressures was determined.
4. At every run, the operating pressure was set to desired pressure level using the brine flow control valve while the feed flow rate was kept at 1.35 ml/sec by adjusting the feed pump valve.
5. After the permeate flux was measured with de-ionized water at different operating pressure, the saline feed solutions were tested. The RO test was conducted with lower feed concentration (2000 ppm) first, and the feed NaCl concentration was gradually increased to determine the RO performance at different NaCl concentrations (4000 and 6000 ppm).
6. In each run, the feed solution was passed through the membrane system for 2 h to reach steady state.
7. After the experiment reached the steady state, the operating pressure was initially adjusted to 100 psi, followed by 150 psi then 200 psi until the pressure reached 250 psi. At high pressure (i.e., above 250 psi), the pump started to fluctuate in delivering pressure, which caused variations in feed pressure.
8. When the operating pressure increased, the feed flow rate required adjustment which was achieved by adjusting the pump flow rate valve and the brine flow control valve carefully. Operating pressure effects the feed flow rate because the feed flow rate was decreased when the brine valve was closed to increase the operating pressure and more time was needed to reach the desired operating conditions.
9. After all experiments were done, the feed solution was drained from the membrane system. Thereafter, de-ionized water circulated through the membrane system for 6 h in order to clean the membrane system from residual salts.
10. Finally, the experiment was shut down by switching the pump to "Off" mode and draining the water from membrane system to keep it clean and dry until next use.

In testing the desalination of the real produced water, the water sample was pre-filtered with an ultrafiltration unit that was carried out in a similar fashion as the RO test. The purpose of the prefiltration was to remove residue oil in the produced water prior to RO desalination in order to prevent potential fouling issues in RO process.

Chapter 4

Results and Discussion

This chapter discusses experimental and predicted results to describe and discuss the findings of the RO membrane performance in terms of salt rejection and permeation flux under various operating pressures (100, 150, 200, 250 psi) and feed salt concentrations (2000, 4000, 6000 ppm). Operating data needs to be collected experimentally for each new kind of membrane and membrane material. According to Kimura and Sourirajan analysis (KSA) approach, the experimental results were used to calculate the pure water permeability constant, A, solute transport parameter ($D_{Am}K_A/\delta$), and mass transfer coefficient, k, which were used to predict the membrane performance at higher operating pressure. The performance of RO membrane using real water samples will also be discussed in terms of permeate flux and salt rejection at different feed concentrations and pressures for different commercials membranes.

4.1 Experiment Results with Simulated Brackish Water

4.1.1 Impacts of Operating Conditions on Salt Rejection

The membrane performance for salt rejection under various pressures and feed salts concentrations was determined experimentally, as shown in Figure 4.1 and Table 4.1. In Figure 4.1 a nonlinear relation between salt rejection and operating pressure for all feed concentrations was observed. For example, the salt rejection at all feed concentrations 2000-4000-6000 ppm shows an increase in salt rejection as operating pressure increases until it reaches 150 psi. Operating pressures higher than 200 psi has very little increase in salt rejection by the membrane.

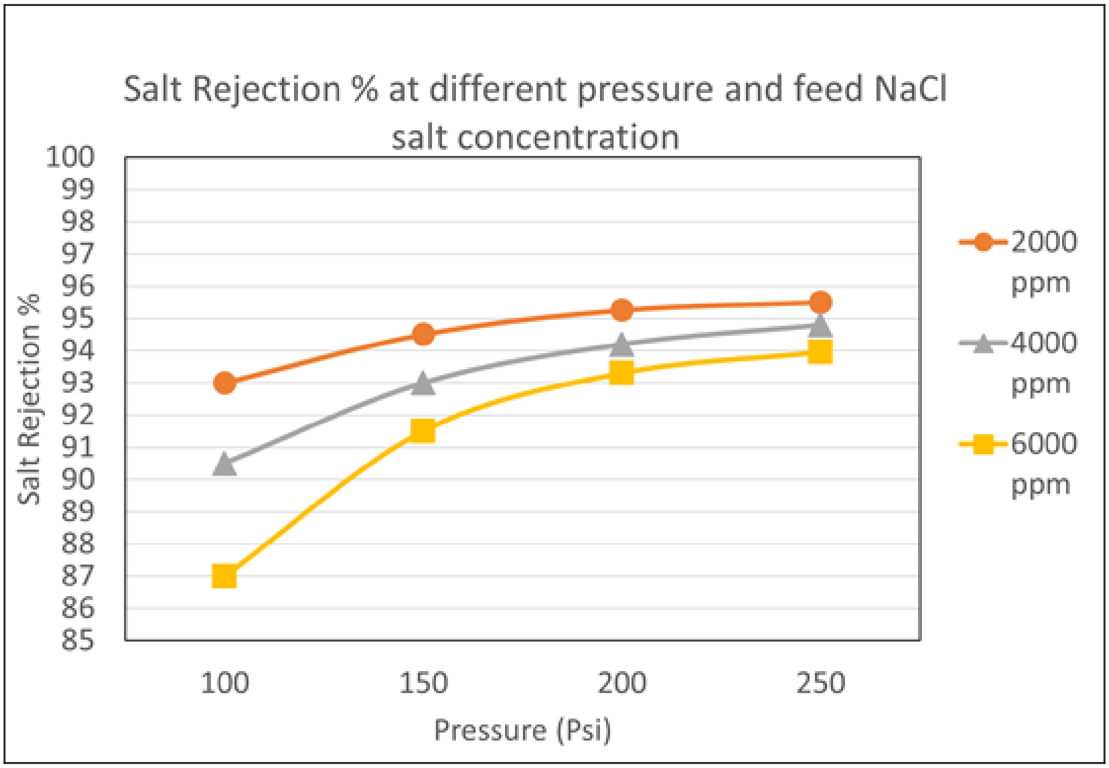

Figure 4.1: Salt rejection % at different pressures and feed NaCl salt concentrations.

The effective operating pressure on salt rejection for low feed salt concentration can be more beneficial within the ranges of 100 psi to 200 psi which are acceptable based on previous research findings [24].

On the other hand, Figure 4.1 shows expected impact of different feed salt concentrations on the salt rejection. The osmotic pressure increases when the feed concentration increases, which reduces the pressure difference that drives the membrane separation. The pressures applied to RO membrane had a higher effect on the salt rejection at higher feed salt concentrations than at lower feed salt concentrations. However, the salt rejection rate did not show significant increasing trend as the pressure increases at 250 psi for all the feed salt concentrations tested, as illustrated in Figure 4.1.

Table 4.1: Salt rejection % at different pressures and feed NaCl salt concentrations.

Concentration of feed water (ppm)	Salt Rejection %			
	Feed Pressure			
	100 psi	150 psi	200 psi	250 psi
2000 ppm	93	94.5	95.25	95.6
4000 ppm	91	92.8	94.2	94.8
6000 ppm	87	91.4	93.2	94

4.1.2 Impacts of Operating Conditions on Permeate Flux

The impacts of operating pressure and feed salt concentration on permeate flux are illustrated in Figure 4.2. The most interesting aspect of Figure 4.2 is that that permeate flux at a given concentration is linear with respect to operating pressure. The linear relationship exists between the permeate flux and the operating pressure for all the different feed concentrations, which indicates the permeation flux is proportional to the driving force for permeation. This finding gives a clear relation of strong effect of operating pressure on permeate flux. There is an increase in permeate flux and the salt rejection approach a limiting value with an increase in operating pressure.

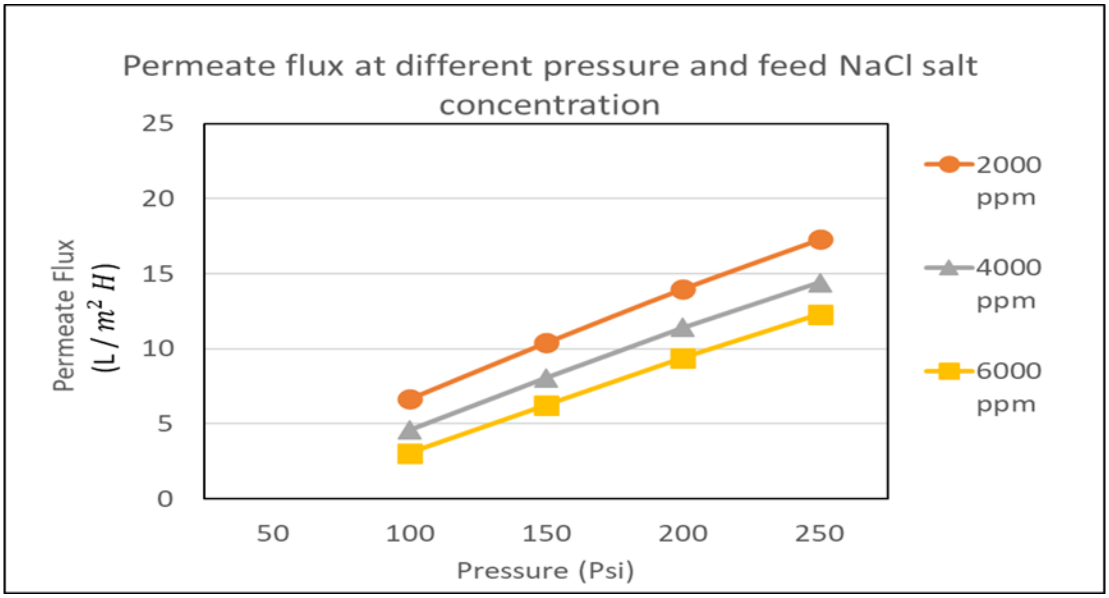

Figure 4.2: Permeate flux at different pressures and feed NaCl salt concentrations.

4.2 Mass Transport Production of the TFC RO Membrane

Figure 4.3 shows that the pure water permeability coefficient of TFC RO membrane in the range of the operating pressures applied remained constant at a feed flow rate ml/sec and room temperature 25 °C. As a result, the experiment findings of testing on pure water permeability indicate there was no compaction effect for the membrane over different operating pressures from 100 to 250 psi. The pure water permeability coefficient of the membrane was 2.17 $\times 10^{-7}$(Kg-mol/m^2 $sec\, kpa$) as calculated using equation 2.3.

The constant pure water permeability indicates a good membrane performance over the experimental operating pressure range across the membrane. However, due to the relatively narrow pressure range, this stability may vary in a wide operating pressure ranges. Thus, the membrane stability for sea water desalination which would operate at much higher pressures should be determined separately. After determining membrane the membrane performance is at certain conditions, the important information about the impact of operating conditions such as (pressure, feed concentration) can be calculated using the transport equations. The mass transport parameters can be used to predict the

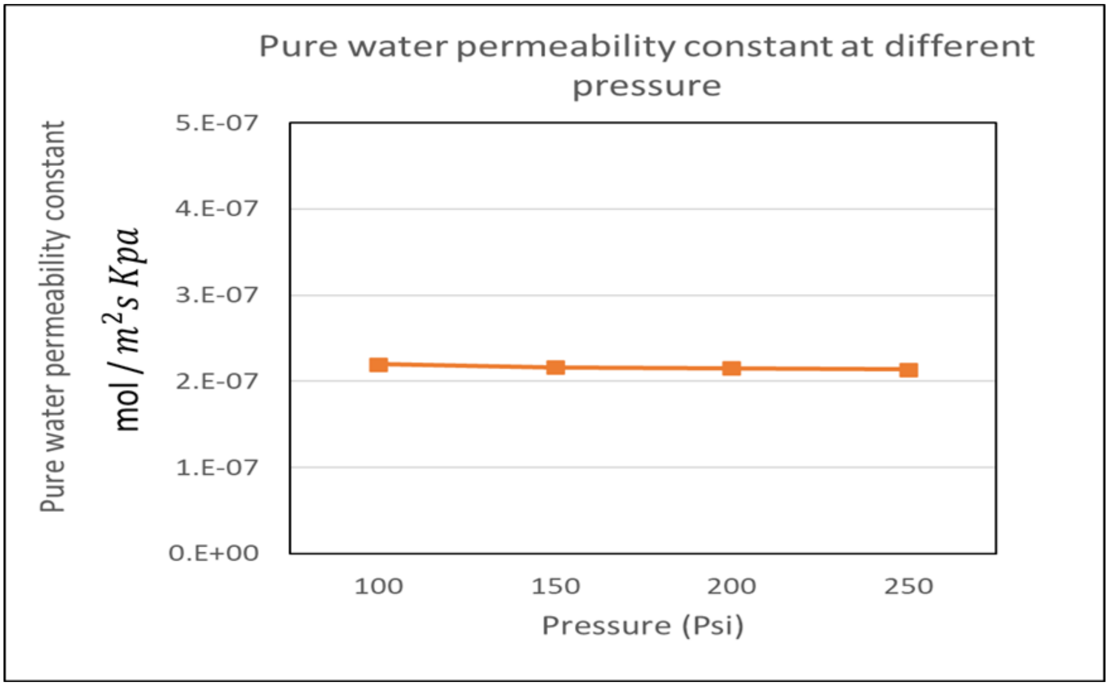

Figure 4.3: Pure water permeability coefficient of RO membranes at feed water flow rate 1.35 ml/sec.

membrane performance of the TFC PA RO membrane at the other operating conditions. These parameters are solute transport parameter ($D_{Am}K_A/\delta$) and mass transfer coefficient, k, in addition to water permeability constant.

Figure 4.4 shows the solute transport parameter ($D_{Am}K_A/\delta$) values continued to decrease as the applied pressure increases and the feed concentration the decreases. The possible reason of this impact on solute transport parameter is due to the concentration difference across the membrane at a high feed concentration is higher than at a low feed concentration, which means salt passage through membrane will be higher [33] [34]. However, at a high pressure, solute transport parameter ($D_{Am}K_A/\delta$) becomes lower. Note the solute transport parameter ($D_{Am}K_A/\delta$) is not strong dependent on pressure based on some work in literature [35] [30]. However, the results here show that the solute transport parameter is affected by the pressure especially at high feed concentration more than low feed concentration.

Figure 4.5 shows the mass transfer coefficient, k, values slightly decrease with increasing applied pressures, whereas, k values increase when the feed salt concentration increases.

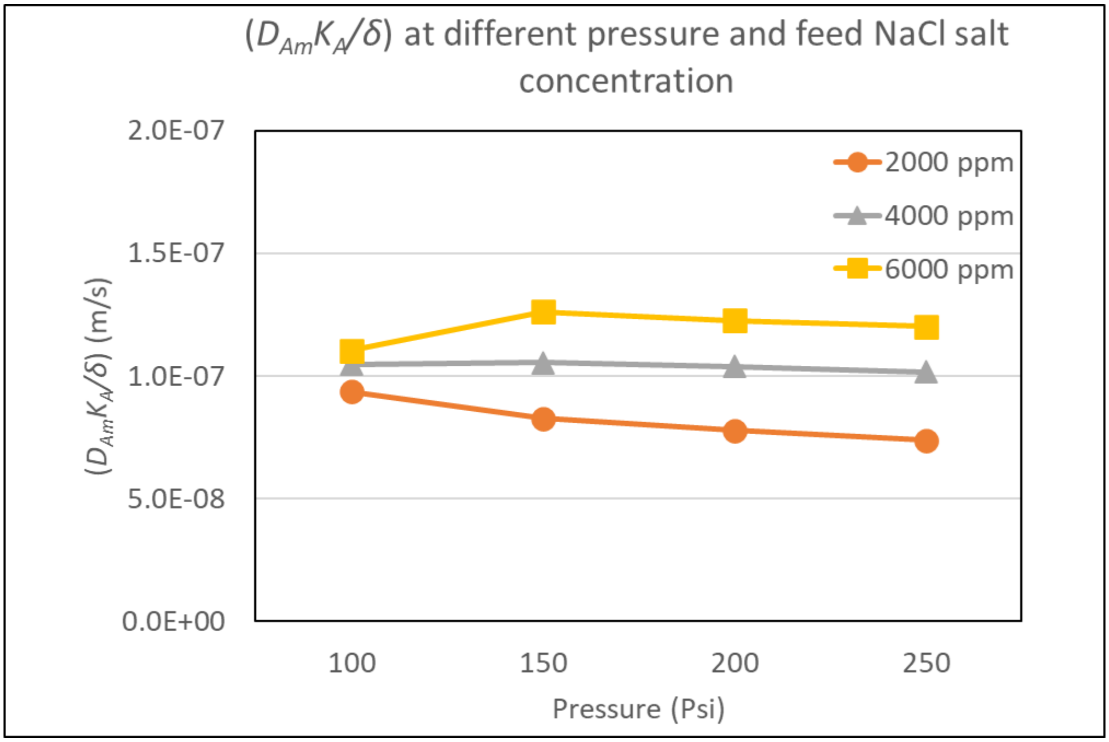

Figure 4.4: $(D_{Am}K_A/\delta)$ at different pressures and feed NaCl salt concentrations.

Consequently, the mass transfer coefficient indicates the low impact of formation of concentration polarization layer. As shown in Figure 4.5, at low feed salt concentration, the mass transfer coefficients are largely constant, which shows independent effect of feed concentration. At a given feed concentration, the mass transfer coefficient is not impacted by operating pressure significantly. This seems to indicate a low effect of membrane compacting. The feed concentration impact on mass transfer coefficient is consistent with previous results [35] [30]. Over the concentrations range, the diffusivity and viscosity of the liquid phase are largely the same for given hydrodynamic conditions relating in an essentially constant mass transfer coefficient, k.

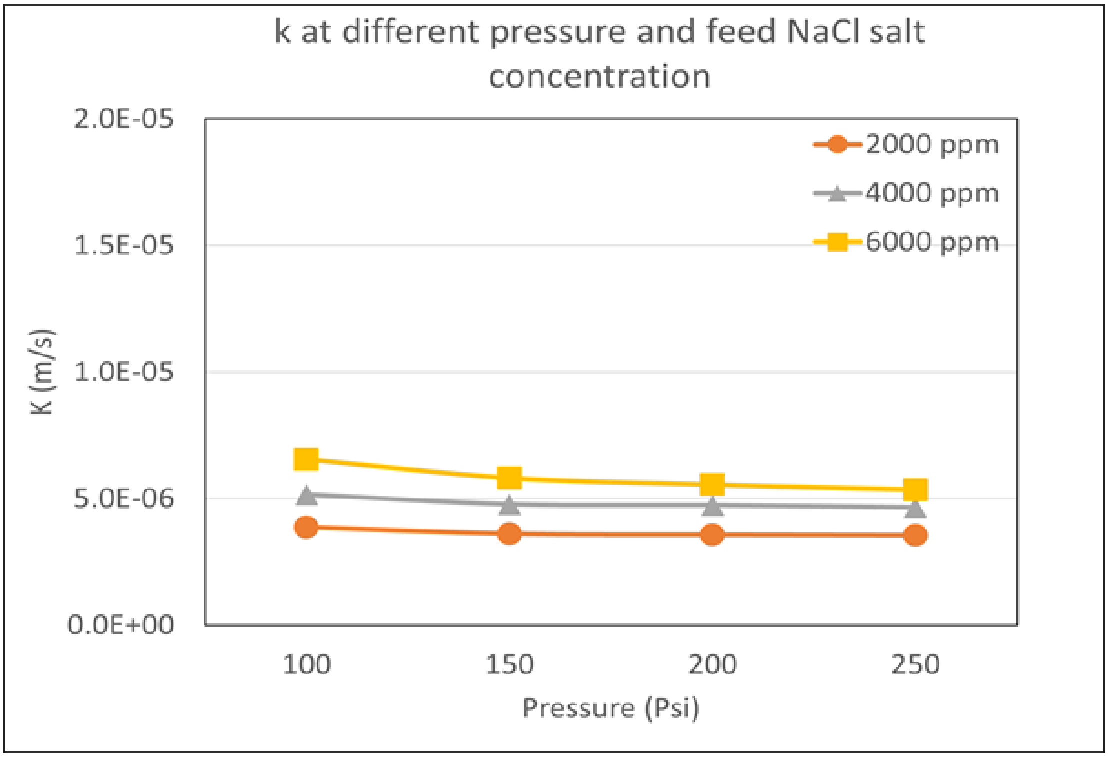

Figure 4.5: k at different pressure and feed NaCl salt concentration.

4.3 Predicting RO Membrane Performance at Higher Pressures

The performance of RO membrane can be predicted for different operating conditions using the mass transfer coefficient, k, and solute transport parameter $(D_{Am}K_A/\delta)$ based on the Kimura and Sourirajan analysis model. As shown in Figures 4.6 and 4.7, the trend of the two parameters estimated by extrapolating the data to higher feed pressures as an approximation.The effects of pressure on mass transfer coefficient, k, and solute transport parameter $(D_{Am}K_A/\delta)$ were estimated based on data over a small range of operating pressures that were obtained experimentally. However, at high pressures, the variation of mass transfer coefficient, k, and solute transport parameter $(D_{Am}K_A/\delta)$ become smaller and solute transport rate reduces. It was predicted that high operating pressures may decline in diffusivity due to membrane compacting. At low concentration, the membrane showed low impact of mass transfer coefficient but a high reduction in solute transport rate.

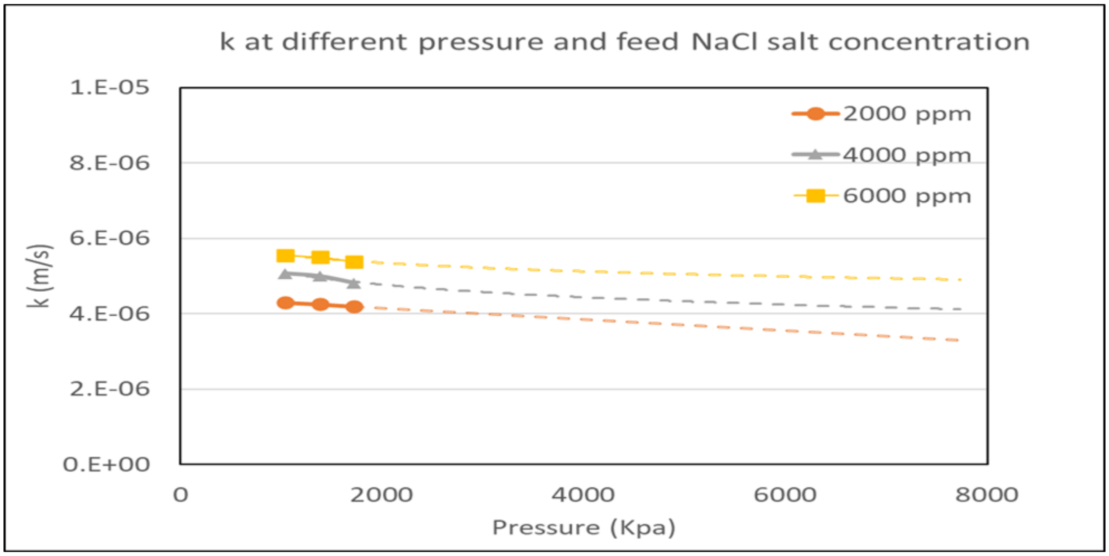

Figure 4.6: The prediction of k values at different pressure and feed NaCl salt concentration.

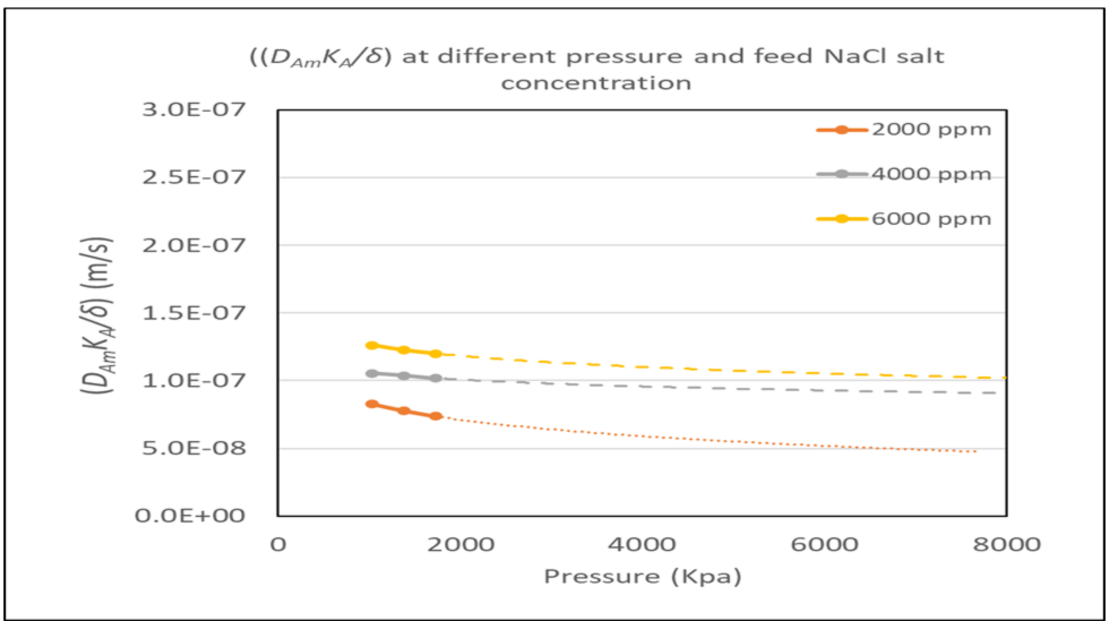

Figure 4.7: The prediction of $(D_{Am}K_A/\delta)$ values at different pressure and feed NaCl salt concentration.

This result can be used to predict the permeability and selectivity of RO membrane at a broader range of operating pressures. However, a high concatenation range is not practical due to more dramatic impact on membrane performance, which needs to be investigated experimentally.

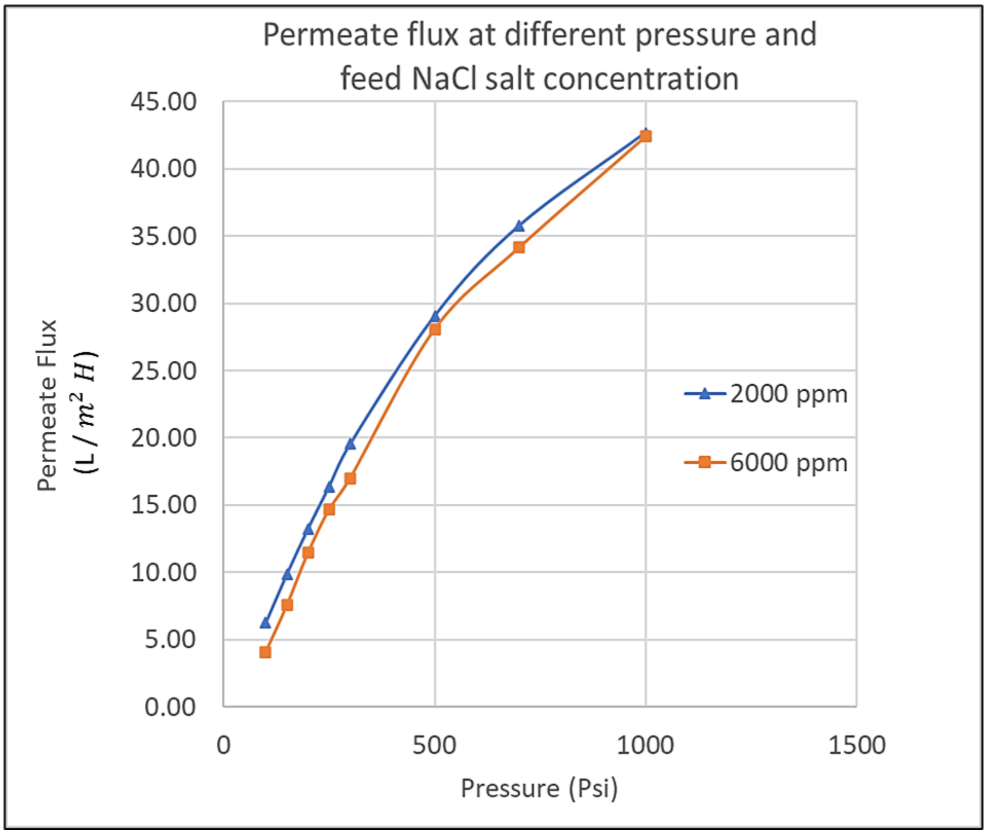

Figure 4.8: The predication of the permeate flux at different pressures and feed NaCl salt concentrations.

The membrane performance at high pressures was calculated. The permeate flux is shown in Figure 4.8. As a result of declining in mass transfer coefficient and solute transport parameter, the permeate flux declined gradually. On the other hand, the salt rejections at low feed concentration were affected solute rejections less significantly at higher feed concentrations, as illustrated in Figure 4.9. The reason for that is the rate of solvent to permeate through membrane is higher than the rate of solute to transport through membrane as operating pressure is increased. Subsequently, the difference of the solvent and solute permeation rate is smaller at low operating pressure than at high operating pres-

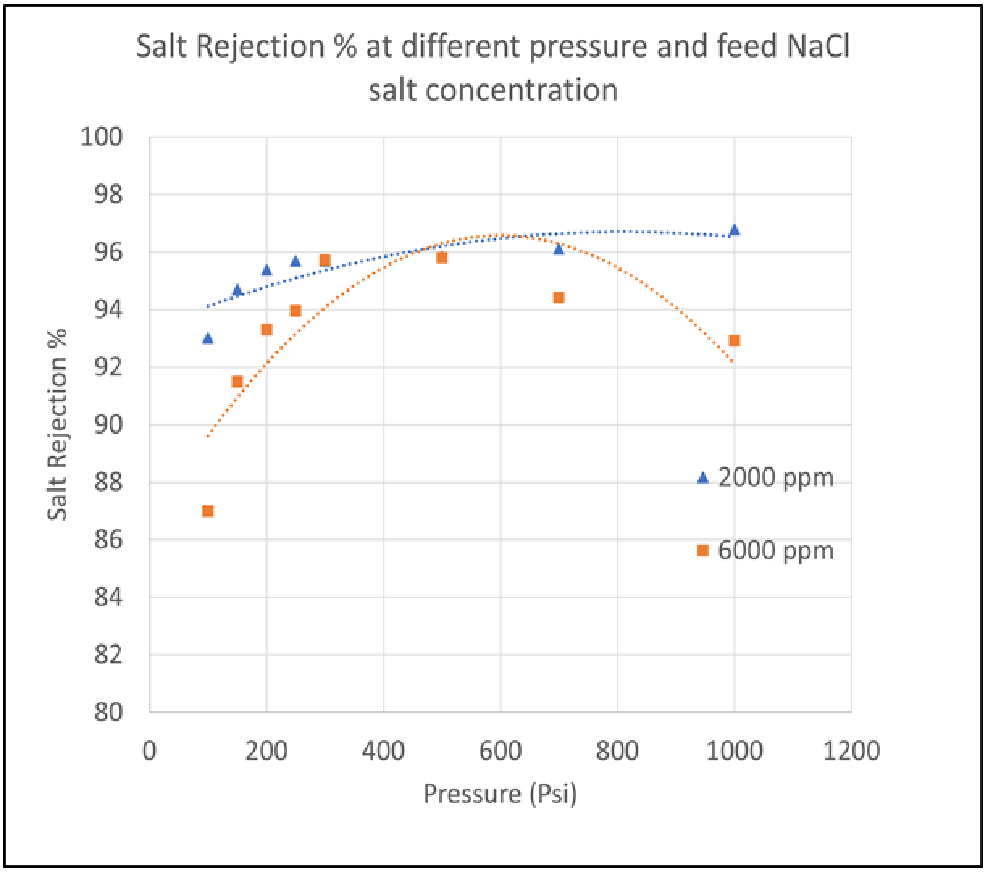

Figure 4.9: The prediction of salt rejection % at different pressures and feed NaCl salt concentrations.

sure. The results indicate acceptable agreements with model calculations and experimental results matched with calculations well.

4.4 Desalination of Produced Water from Oil and Gas Productions

Real water samples from oil and gas production were supplied by Matrix Solutions, the samples water were produced water from oil and gas production in Western Canada. To evaluate the performance of the RO technology for desalination of Nacl brackish water, two spiral wound membrane modules (TFC-1812-75 and TW30-1812-36) manufactured by Hangzhou Water Treatment Center and Dow Filmtech, respectively, were used initially. Here the membrane spec numbers "1812" mean a norminal module diameter of 1.8 in and length of 12 in, while "75" and "36" represent the norminal flow rating of 75 and 36 GPD (gallons per day), respectively.

Figure 4.10 shows the water flux and salt rejection of simulated water at different salt contents for the TFC-1812-75 membrane module. The feed salt concentration was varied from 0 (pure water) to 3.6 wt%, to cover a broad range of salt content in produced water commonly concentrated in the oil and gas processing. As expected, with an increase in the salt content in water, both water flux and salt rejection decreased, while a higher operating pressure helped improve the desalination performance of the TW30-1812-36 membrane module is shown in Table 4.2. However, the flux obtained was considerably lower than TFC-1812-75 (which is not surprising because TFC-1812-75 had a higher water how rating). Therefore, in subsequent experiments with real water, TW30-1812-36 was not used. Instead, a few flat membranes were tested along with TFC-1812-75.

Table 4.2: Water flux and NaCl rejection data of spiral-wound membrane TW30-1812-36. (Test conditions: Temperature 31.5 C ; Flow rate: 95 L/h).

Membrane		RO Element TW30-1812-36(FILMTECH MEMBRANE)			
#	Concentration of feed water (wt%)	Feed Pressure (MPa)			
		0.3 (MPa)		0.6 (MPa)	
		Flux (LMH)	R (%)	Flux (LMH)	R (%)
1	0	0.36	-	0.80	-
2	0.189	0.14	49.4	0.52	76.8
3	1.159	0.078	25.8	0.24	37.4
4	2.058	0.077	14	0.21	22.4
5	2.950	0.072	8.8	0.19	14.3
6	3.614	0.070	8.4	0.19	12.4

Table 4.3 shows the results for desalination the real produced water. Because the

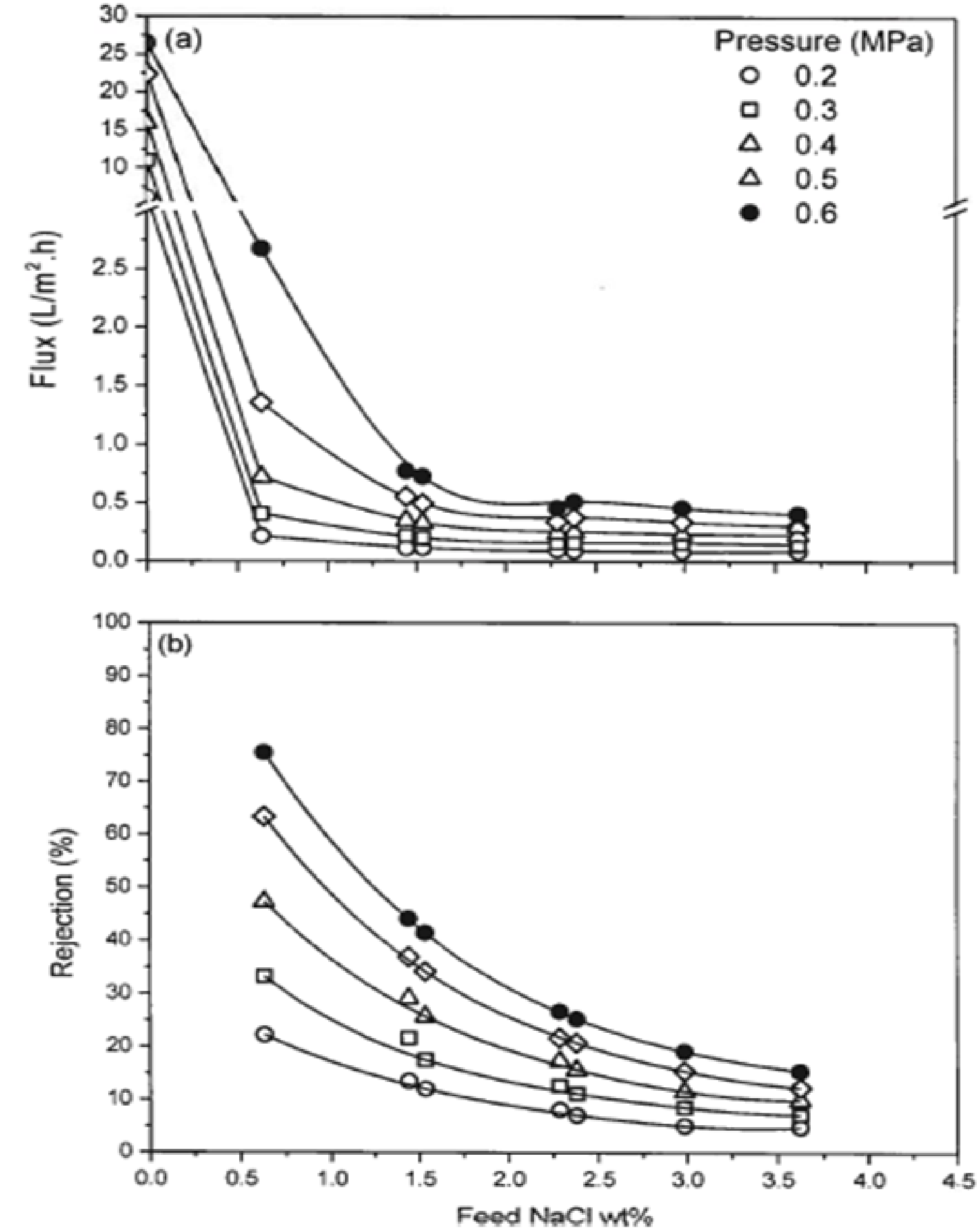

Figure 4.10: Water and salt rejection at different feed salt concentrations for spiral-wound membrane TFC-1812-75 under different pressures. Feed flow 95 L/h , temperature 31.5 C.

Table 4.3: Separation performance of different commercial RO membranes.

#	Membrane	Pressure (MPa)	Feed Solution	Flux ($L/m^2\ h$)	Salt Rejection %
1	Spiral-Wound (Hangzhou)	0.3	1.5 wt% Simulated	0.20	17.5
2			1.5 wt% Real	0.11	18.7
3		0.6	1.5 wt% Simulated	0.73	41.4
4			1.5 wt% Real	0.43	39.9
5	Flat Sheet-1 (Sepro)	0.6	1.7 wt% Simulated	0.53	45.5
6			1.7 wt% Real	0.25	86.1
7	SPET RO-3		1.5 wt% Real	0.23	56.1
8	SPET RO-4		1.6 wt% Real	0.50	68.9
9	SPET RO-6		1.7 wt% Real	0.28	74.4
10	HRX- RO		1.6 wt% Real	0.31	73.0
11	FLAT SHEET (Hangzhou)	0.6	1.7 wt% Real	0.76	36.5
12		0.3	1.7 wt% Simulated	0.46	18.8

original produced water contains small amounts of oil droplets and particulate matters, the produced water was pretreated with an ultra-filtration membrane with a molecular weight cut off 10,000 prior to the RO desalination. For comparison, the desalination performance of the membrane was also determined experimentally for simulated feed water (NaCl+H2O) that had the same salt NaCl content. It was shown that the membrane performance for desalinating the real water was lower than the membrane performance for desalinating the simulated clean water at the same salt concentration in the feed solution. This trend applied to all the membranes tested, including the flat sheet membranes. Therefore, it appeared that pretreatment of the feed water to remove water residue and particulate matter was critical to minimize membrane fouling in the RO for desalination. Nevertheless, the potential of using RO for desalinating the brackish water produced in oil and gas processing was demonstrated, through more detailed studies are required to determine the techno-economic feasibility of the process in the view of huge volumes of the produced water for practical applications.

Chapter 5

Conclusion

5.1 General Conclusion

RO membrane will continue to be used for desalinating sea, brackish and ground water. Understanding the transport process in RO membranes can lead to prediction and improvement on its performance at various operating conditions. In the present study, TFC polyamide RO membrane performance for desalinating brackish water was investigated and its performance at extended operating condition ranges was predicted. In the RO experiments, different operating pressures (100 -250 psi) and feed concentrations (2000-6000 ppm) were used as normal operating conditions for evaluating the TFC polyamide RO membrane performance for desalinating brackish water. Firstly, the membrane performance was analyzed in terms of water flux and salt rejection. Based on the experimental results, the membrane performance was predicted by using Kimura and Sourirajan approach model to calculate salt transport parameters and mass transfer coefficients. Based on the experimental results, the membrane performance was predicted by using Kimura-Sourirajan model to calculate salt transport parameters and mass transfer coefficient. Then, the transport parameters were used to predict the membrane performance at higher operating pressures. The applicability of RO membrane for processing the actual produced water from oil and gas production was evaluated by carrying out the desalination of brackish water using several membranes, including flat membranes and spiral wound membrane modules.

It was showing that operating pressure and feed concentration had a major impact on water permeation and salt rejection in the membrane, and the results were in general in good agreement with previous similar studies. Moreover, the solute transport parameter was shown to be dependent of concentration difference between feed and permeate. However, a clear understanding of how operating pressure contributes quantitatively to the salt transport is still lacking. Nevertheless, the results showed that the operating pressure had a negative impact on mass transfer coefficient and solute transport parameter and the impact was more significant at higher feed salt concentrations. The RO technology was shown to be effective to desalinate the produced water from oil and gas productions, through the performance was lower than what would be achieved in desalinating simulated clean water at the same salt concentration. This suggests that pretreatment of the ”real” water was very important to the RO operation.

5.2 Recommendations

1. The maximum operating pressure was limited by the membrane system setup at high feed flow rate. As a result, it is recommended to modify the membrane system that has capability to operate the RO membrane system at wide range of pressures and flow rates.

2. The model for the prediction of performance of reverse osmosis membrane for binary system has been discussed here, and a foundation for further progress with different component can be used. Based upon this work, the prediction of the membrane performance should be extended to cases where impurities may be present.

3. In this study, the model for the prediction of performance of reverse osmosis membrane was investigated based on a single solute (NaCl) system. However, the simulated brackish water does not represent the real brackish water, which contains other mineral compounds in addition to the major component NaCl. Therefore, it is recommended to improve the predication method by using a real brackish water samples as well. Moreover, the stability of membrane performance needs to be investigated to predicted the life time performance efficiency, which was attempted by many studies before [35] [36].

4. The potential of using the RO membrane to process produced water from oil and gas production was demonstrated in this study. However, more detailed studies are needed to evaluate the techno-economic feasibility of the process because of the large quantity of the feed water to be treated for commercial applications.

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