ADSORPTION AND CHEMICAL CLEANING PROCESS OF ANIONIC AND NON-IONIC SURFACTANTS ON THE MEMBRANE SURFACE THROUGH THE FORWARD OSMOSIS PROCESS: APPLICATION FOR WATER REUSE

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กระบวนการดูดซับและกระบวนการล้างทางเคมีของสารลดแรงตึงผิวชนิดมีขั้วและไม่มีขั้วบนพื้นผิวของเมมเบรนที่ผ่านกระบวนการฟอร์เวิร์ดออสโมซิส: การประยุกต์เพื่อนำน้ำกลับมาใช้ใหม่

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ไกรวิชญ์ เรืองฤาหาร : กระบวนการดูดซับและกระบวนการล้างทางเคมีของสารลดแรงตึงผิวชนิดมีขั้วและไม่มีขั้วบนพื้นผิวของเมมเบรนที่ผ่านกระบวนการฟอร์เวิร์ดออสโมซิส: การประยุกต์เพื่อนำน้ำกลับมาใช้ใหม่. (ADSORPTION AND CHEMICAL CLEANING PROCESS OF ANIONIC AND NON-IONIC SURFACTANTS ON THE MEMBRANE SURFACE THROUGH THE FORWARD OSMOSIS PROCESS: APPLICATION FOR WATER REUSE) อ.ที่ปรึกษาหลัก : รศ. ดร.สุธา ขาวเธียร

กระบวนการฟอร์เวิร์ดออสโมซิสเป็นเมมเบรนเทคโนโลยีที่กำลังได้รับความสนใจ และมีการประยุกต์ใช้กระบวนการนี้อย่างแพร่หลายเพื่อผลิตน้ำสะอาด งานวิจัยในครั้งนี้มีวัตถุประสงค์ในการศึกษาพฤติกรรมการเกิดชั้นของสิ่งสกปรกและกลไกที่เกิดขึ้นบนพื้นผิวของเมมเบรน (osmotic membrane) ที่ถูกคุมด้วยสารลดแรงตึงผิวชนิดมีขั้วลบ (sodium dodecyl sulfate, SDS) และไม่มีขั้ว (nonylphenol ethoxylate, NP-40) รวมถึงกระบวนการทำความสะอาดพื้นผิวของเมมเบรน โดยการศึกษาผลกระทบที่จะเกิดกับกระบวนการฟอร์เวิร์ดออสโมซิส จะมีการเดินระบบภายใต้สภาวะที่แตกต่างกัน คือ ความเร็วในการไหลของสารละลาย ค่าความเป็นกรด-ด่างของสารละลาย และปริมาณความเข้มข้นของสารลดแรงตึงผิว ส่วนการศึกษากระบวนการทำความสะอาดพื้นผิวจะใช้น้ำปราศจากไอออน (Deionized-water), 0.1 M NaCl และ alkaline solution (NaOH, pH 11) ผลการศึกษาพบว่าอัตราการแพร่กระจายของโมเลกุลของน้ำผ่านออสโมติกเมมเบรน (osmotic membrane) จะมีอัตราที่เพิ่มขึ้นด้วยการเพิ่มความเร็วในการไหล การเพิ่มค่าพีเอช (pH) ของสารละลาย และการเพิ่มปริมาณของสารลดแรงตึงผิว และผลการทดลองยังพบอีกว่าการสะสมประจุลบบนผิวเมมเบรนอย่างต่อเนื่องยังทำให้กระบวนการแพร่ของโมเลกุลของน้ำเพิ่มขึ้น ส่วนการศึกษาการแพร่กระจายตัวของโมเลกุลของเกลือจะลดลงหลังจากเติมสารลดแรงตึงผิวลงในระบบเนื่องจากชั้นสารลดแรงตึงผิวจะทำหน้าที่เป็นตัวต้านทานการแพร่กระจายของเกลือในระบบ ส่วนในกระบวนการทำความสะอาดพื้นผิวผลการวิจัยพบว่าการเพิ่มพีเอช (pH 11) จะทำให้ประสิทธิภาพของระบบสูงขึ้นที่สุดเนื่องจากการเพิ่มพีเอช (pH 11) จะช่วยเกิดการแพร่กระจายของน้ำมากขึ้น

สาขาวิชา วิศวกรรมสิ่งแวดล้อม ลายมือชื่อนิสิต ....
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Forward osmosis (FO) process, an attractive membrane technologies, have been widely studied and applied in many fields to manufacture the clean water. This work, we focused on the fouling behavior and mechanisms of forward osmosis (FO) fouled by sodium dodecyl sulfate (SDS) as anionic surfactants and of nonylphenol ethoxylate (NPE, NP-40) as nonionic surfactant, including cleaning process to recover the system. FO process was run under different operating conditions (cross flow velocity, pH of feed solution, surfactant concentration). In addition, deionized-water (DI), 0.1 M NaCl, and alkaline solution (NaOH) were applied as agents for the cleaning process. The results revealed that the diffusion of water molecules increased with cross-flow velocity, feed solution pH, and surfactant increasing in both single surfactant and mixture surfactant. In addition, deposits of negative charge on the membrane surface induced the diffusion of water molecules, whereby increasing FO performance. Contrariwise, the diffusion in salt molecules decreased after adding the surfactant into the feed solution due to the surfactant layer performing as a resistance, resulting in the reduction of salt flux and increasing of reversal salt selectivity. In terms of cleaning process, the findings significantly indicated that the highest performance was increased when the FO system was operated at high pH (pH 11) of feed solution due to negatively charged promoted the increasing in diffusion of water molecules.

Field of Study:	Environmental Engineering	Student's Signature ....
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Kaiwit Ruengruehan

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIX TABLES

CHAPTER I

INTRODUCTION

1.1 Introduction

According to the increasing of the population and economic development, the demand of freshwater is becoming to be farther all area of the world but it is ambivalent the water source quality and quantity. A problem of water source is generally contaminated with the various types of the pollutants that can be easily found in the environmental system. Therefore, it is difficultly searching a proper source of clean water to continuously support the water supply for consumption. Over the past decades, a large city has become increasingly aware of the role fresh water plays as a critical resource. In addition, the increasing of amounts of fresh water will be required in the future because of the increase in population. As the reason, it is necessary to search and find a new water source for consumption as well as the technical development. Membrane technology is widely applied in the various fields such as water improvement, water treatment, and wastewater reclamation due to it highly separates a contaminants, and high water productivity. The advantages of the membrane process that can solve a wide range of contaminate separation, and it might be distinguished by the range of substances separated. The pollutants can be removed with the selective permeable membrane that is a barrier between the contaminated solution and clean water. In addition, the important thing of the membrane separation is the driving force that is applied to push the water molecules from the feed solution to the clean water. The driving force can be generated by a gradient of pressure, chemical potential, and electrical potential across the membrane. Over the past decade, the various types of the membrane processes have been developed, and new membranes process are constantly emerging from academic, industrial, and government laboratories. However, there are four commercial popular types of membrane that are commonly applied in the water and wastewater treatment by using a pressure-driven as a driving force, namely, microfiltration (MF), ultrafiltration (UF), nano-filtration (NF) and reverse osmosis (RO). The gradient pressure-driven is used to extract the freshwater though the membrane. However, as considered the performance of the membrane, microfiltration and ultrafiltration are only able to separate a particulate matters, while NF and RO membranes retain solutes as water permeates through the membrane. Reverse osmosis (RO) is commonly selected for the water and wastewater treatment. In addition, RO generally requires highly applied a driving force (pressure-driven) around 300-500 psi to push the water from feed solution through the selectively permeable membrane. More energy need to be applied for the RO process, and these mean more cost needed to be supported. Recently, Forward Osmosis (FO) utilizes an osmosis pressure that the water moves from a low concentration (feed solution) to a high solution (draw solution) though a selectively permeable membrane. The driving force of FO process is naturally generated by osmotic pressure gradient of solution that is the different concentration between a high concentration and low concentration, while RO process uses a hydraulic pressure as a function of a driving force. There are many potential advantages of FO process such as the FO process used lesser energy requirements than RO process, good product water quality, used low hydraulic pressure to operate, and low fouling as compared the applied hydraulic pressure(Cath et al., 2006b) (Cath et al., 2006b, McCutcheon et al., 2005). Therefore, the FO process is widely applied in the various fields. Several have been reported that FO process was used the food industry (Petrotos and Lazarides 2001), separation emulsion oil (Duong and Chung 2014), forward osmosis membrane bioreactor (FO-MBR) (Achilli et al., 2009, Christensen and Plaumann 1981), removal boron and arsenic in wastewater (Jin et al., 2012), reclamation of water from drilling waste to facilitate beneficial water reuse(Cath et al., 2006b). Membrane fouling is commonly generated and attached on the membrane surface during(Xing et al., 2003) the filtration process, and it plays a main role in the decreased performance of filtration process. Membrane fouling is generally referred to as consisting of substances, which are dissolved in both the water and wastewater. Typically, membrane fouling can be distinguished four types of the fouling, namely organic (oils, polyelectrolytes, humic substances, surfactants, etc); colloidal particles (clays, flocs, cake formation of colloid or solutes, etc;); biological (the accumulation or growth of microbiological organisms, bacteria, fungi); scaling (precipitation of inorganic salts, particulates of metal oxides). Including, the membrane fouling, which are dissolved and undissolved molecules, particulate matter, salt precipitates, and microorganisms, and the membrane fouling can be easily affected the RO process (Childress and Elimelech 1996, Kim et al., 2006). As reason, the understanding of membrane fouling in the FO process need to be more investigated. During the membrane filtration, the properties of membrane fouling can be reacted with the chemical on the membrane surface. The main interaction of the membrane fouling and the membrane surface are the adsorption of organic materials from the feed water such as humic acid substances, proteins, polysaccharides, surfactants, and the reaction of chemical fouling depends on hydrophobic interaction and electrostatic interaction between organic materials in the feed water and membrane surface (Duong and Chung 2014, Lee et al., 2011, Rosen and Kunjappu 2012). Several researches have been reported that the interaction of membrane fouling on the membrane surface can be reduced the performance of membrane process, and the attachment and coating of membrane fouling agent are main essences (Achilli et al., 2009, Ang and Elimelech 2008). In addition, the adsorption and attachment of fouling onto the membrane surface leads to lower performances in the RO process (Ng et al., 2006), and adsorbed membrane fouling onto the membrane surface during the filtration process is a significant mechanism for the decreased performance in filtration (Li et al., 2007). Surfactants are an organic compounds used in everyday life and are essential components in many industrial processes. There are many products used a surfactants as a raw material, namely, a household detergents, personal care formulations, industrial and institutional washing and cleaning, as well as numerous technical applications such as textile auxiliaries, leather chemicals, agrochemicals (pesticide formulations), metal and mining industry, plastic industry, lubricants, paints, polymers, pharmaceutical, oil recovery, pulp and paper industry (Myers 1999). After use, residual surfactants and their degradation products are discharged to sewage treatment plants or directly to surface waters, and it dispersed into different environmental compartments. Due to their widespread use and high consumption, surfactants and their degradation products have been detected at various concentrations in surface waters, sediments and sludge-amended soils (Basar et al., 2004, Burke et al., 1975, Shiau et al., 1994). Molecules of the surfactant can be reacted the properties of a substance in the environment. Kaya et al.(2006) stated some surfactants are harmful to human beings, fishes, vegetation, causing foams of the rivers, effluent treatment plants, furthermore, it reduce the quality of water (Kaya et al., 2006, Rao and Dube 1996). Nowadays, there are the technologies that are widely applied to remove the contaminated surfactant in the wastewater have been reported (Kaya et al., 2006). Several technologies have been widespread applied such as electrochemical oxidation and chemical precipitation (Shiau et al., 1994), adsorption (Das Purakayastha et al., 2005), photo-catalytic degradation (Kowalska et al., 2004), biological methods (Lundahl and Cabridenc 1978) and membrane technology (Basar et al., 2004, Baudequin et al., 2014b, Kaya et al., 2006). As reviewed, the membrane technologies have been applied to remove the contaminated surfactants in water and wastewater. In addition, a various types of surfactant that are removed by membrane filtration such as linear alkyl benzene sulfonate and cetyl trimethyl ammonium bromide (MF), sodium dodecyl sulfate and sodium dodecylbenzene sulphonate (UF), linear alkyl benzene sulfonate and sodium dodecylether sulfate (NF), fluorinated surfactant and sodium dodecyl sulfate (RO) (Amy and Cho 1999, Basar et al., 2004, Baudequin et al., 2014b, Boussu et al., 2007, Doulia et al., 1997, Jönsson and Jönsson 1991). In addition, the interaction of surfactant with the membrane surface could be occurred in the various ways. Kaya et al. (2006) stated the adsorption of the surfactant on the membrane surface is a main mechanism of membrane filtration(Kaya et al., 2006, Kaya et al., 2011). While coating on the membrane surface of surfactant molecules that can be changed the properties, and reduced the performance of membrane process (Baudequin et al., 2011, Baudequin et al., 2014b). However, the adsorption of the surfactant does not investigate in the FO process. Therefore, it is interestingly research to observe the phenomena, effect of surfactant in the FO process. The removal of membrane fouling on the surface is one of the important processes due to the performance is reduced with the increasing of membrane fouling on the membrane surface with long-term operation, and it is inevitable. Chemical cleaning process is widely applied to remove the membrane fouling on the membrane surface, and variously chemical cleaning agents are commonly used to clean membranes such as alkaline solutions (NaOH pH 11.0), metal chelating agents (EDTA), salt (NaCl) (Macedonio et al., 2012). Furthermore, the selected chemical agent should be less effected the properties of membrane, safety, low cost and ability to be washed/removed with water, loosen and dissolve the foulants, keep the foulant in dispersion and solution form, and avoid new fouling on the membrane surface (Kuzmenko et al., 2005, Lin et al., 2010, Madaeni and Samieirad 2010). The mechanism of membrane fouling cleaning with the proper chemical agent needs to be challenged.

1.2 Research objectives

The overall objectives of this research are to investigate the phenomena and performance of FO process with the surfactants and insights about the possibility of applying separated anionic and non-ionic surfactants in wastewater. The specific objectives are as follows:

1. To investigate the performance, behavior of flux decline, product water quality and the reverse salt of feed solution with anionic and non-ionic surfactants by using FO process.
2. To investigate the effect of humic acid (HA) molecules, colloidal particles, and combined with the surfactant on the FO process.
3. To investigate the change properties of the membrane surface after interaction with anionic, non-ionic and mixed surfactant on the membrane surface.
4. To investigate the change of morphology and performance of membrane after cleaning process by chemical agents (0.1 M NaCl and NaOH (pH 11.0).

1.3 Scope of the study

To be accomplished the above objectives, the following tasks are undertaken.

1. FO process was conducted to find out its effectiveness for anionic, non-ionic, and combined surfactants. The parameters influencing the membrane fouling, adsorption of surfactants (anionic, non-ionic, combined surfactants), the change of hydrophobic of membrane surface by contact angle measurement (virgin and fouled membrane), and morphology of membrane surface were investigated.
2. The experiments were conducted to identify and describe the behavior and mechanisms of surfactants of FO process such as the adsorbed anionic, non-ionic, and mixed surfactants onto the membrane surface, the water flux, salt flux, the proper chemical agents (0.1 NaCl and NaOH), impact of colloidal particles and humic acid (HA) molecules.

3. The initial volume of feed solution was 4L, and the initial volume of the draw solution was 2 L. The temperature was controlled at 25±2°C, and the constant pH solution both feed and draw solution in the range of 6.5-7.5. A gear pump was applied in this study, and the flow rate was controlled at 0.48, 0.92, 7.03 and 10.5 cm/s, maintained the same for both feed and draw sides during each experiment. Each experiment was run for 8.0 h. The membrane cell was a rectangular plate-and frame unit, with a rectangular channel 7.7 cm long, 2.6 cm wide, and 0.3 cm high.

CHAPTER II

LITERATURE REVIEW

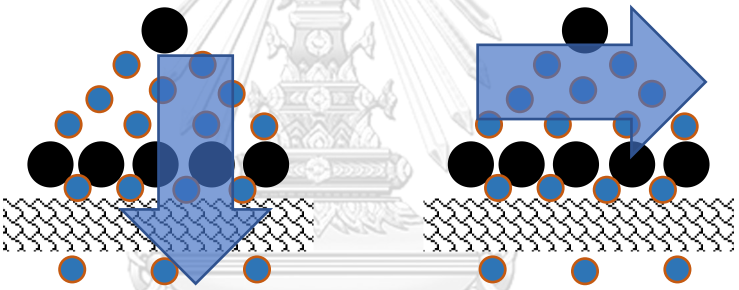
2.1 Membrane separation technology

2.1.1 Introduction

The highly demand of fresh water all areas of the large city in the world; it is necessary to search innovative technologies to produce the clean water for the consumption. Membrane technology is generally selected to separate the pollutants that contaminated in the water and wastewater and it relies on the physical separation. Membrane filtration processes have been widely applied to separate the contaminants in the water and wastewater to produce the clean water for consumption, and it has a wide range of application. The transportation of water in the membrane filtration needs used a driving force that is generally generated by some potential pressure, temperature, concentration or electric potential (Mulder 1991). In the membrane technologies, it can be operated in the two main flow configurations of membrane processes: dead-end filtration and cross-flow filtrations as presented (Figure 2.1). A dead-end filtration process, the influent of feed solution continuously moves to the membrane surface and the contaminants can be easily accumulated on the membrane surface. The deposition of membrane fouling on the membrane surface can be reduced the performance due to the pore blocking and cake formation by the solutes and particles in the feed solution. While a cross-flow membrane filtration process, the direction of feed solution flows parallel to the membrane surface (Figure 2.1). The deposition of the membrane fouling is difficult to generate on the membrane surface due to the membrane fouling are sheared off by the influent flow. Therefore, the accumulation of membrane fouling on the membrane surface in the cross-flow filtration is generally less affect as compared with the dead-end filtration.

2.1.2 Types of commercial membrane

Due to the continuously increase demand of the membrane process that is widely applied in a various fields to separate the contaminants in the water and wastewater. The improvement characteristic and performance of the membrane technologies is extensively increased. At the present, there are four commercial types pressure driven membrane process that are commonly applied in the membrane separation process: namely; microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). The hydraulic pressure is normally used for these types of membrane as a function of the driving force. In addition, the performance of the membrane is typically depended on the molar masses, particle size, chemical affinity, interaction with the membrane (Xing et al., 2003).



a) Dead end filtration b) Cross-flow filtration

Figure 2.1 Schematic diagram of two different configuration for membrane filtration (Cheremisinoff 2002)

The composition of materials that consisted of the structure of the pressure driven membrane process can be distinguished. Tables 2.1 and Table 2.2 were briefly summarized the types, structure of pressure driven membrane process, pore size of the membrane, driving force of process, and mechanism.

Microfiltration (MF) is a pressure-driven membrane process, which removes a particles size between 0.025-10 µm though the micro pores of membrane. The typical pore sizes ranges of microfiltration membrane are 0.1 to 10 µm, and the usually applied hydraulic pressure is lower than 0.20 MPa to push the particles pass through the microfiltration membrane (de Morais Coutinho et al., 2009). The structure of the MF membrane is generally made form a polymer, and it consists of two layers (the dense layer and porous layer). The top of the surface layer is dense layer, and the intermediate of the layer is a porous that is linked with the supporting components. Several researches have been reported microfiltration process can be separated the particles, bacteria and organic matters in the water and wastewater (Campos et al., 2002, Doneva et al., 1998). Furthermore, the MF process was usually selected in the various fields as a pre-treatment process such as food industry, biotechnology, the treatment of oil, municipal wastewater reclamation, anoxic pond effluent treatment and toxic component removal from drinking water (Al-Malack et al., 1998, Han et al., 2002). Summary of microfiltration is illustrated in Table 2.3.

Table 2.1 Comparison of membrane structures (Cheremisinoff 2002)

Technology	**Structure**	**Driving Force**	**Mechanism**
Microfiltration	Symmetric microporous (0.02-10 um)	Pressure, 1-5 atm	Sieving
Ultrafiltration	Asymmetric microporous (1-20 nm)	Pressure, 2-10 atm	Sieving
Nanofiltration	Asymmetric microporous (0.01-5 nm)	Pressure, 5-50 atm	Sieving
Reverse Osmosis	Asymmetric with homogeneous skin and microporous support	Pressure, 10-100 atm	Solution diffusion

Table 2.2 Membrane materials and characteristics (Cheremisinoff 2002)

Technology	Materials	Polar Character
Microfiltration	Polypropylene (PP) Polyethylene (PE) Polycarbonate (PC) Ceramic (CC)	Non-polar Non-polar Non-polar
Ultrafiltration	Polysulfone (PSUF)	Non-polar
	Dynel	Non-polar
	Cellulose acetate (CA)	Non-polar
Nanofiltration	Polyvinylidene (PVDF)	Polar
Reverse Osmosis	Cellulose acetate	Polar
	Polyamide	Polar
	Nylon	Polar

Ultrafiltration (UF) is a membrane separation process. The pore sizes of the UF membrane is smaller those pore sizes of the MF membrane that can be separated a small size of the particles in the water and wastewater. In other words, the performance of the UF process is better than the MF process. In addition, the molecular size of suspended solid that can be separated with membranes ranges from 10^3 to 10^6 Da, and the water and the lower molecules weight can be passed though the UF membrane (Hinkova et al., 2002). The composite of the UF membrane can be made from different polymers, including cellulose acetate (CA), polyvinyl chloride (PVC), polyamides (PA) and polysulfone (PS) (Cheremisinoff 2002). There are commercial three types of UF membrane that usually use in the water and wastewater treatment such as hollow fibres, tubular membrane, and spiral wound membrane module. The UF membrane has been generally applied for the industry process such as purification of food materials, separation of proteins in the food and dairy industries, removal of toxic heavy metals, recovery of valuable contaminants in process waste streams and production of potable water

(Bhattacharyya et al., 1974, Christensen and Plaumann 1981, Revchuk and Suffet 2009). Summary of ultrafiltration is shown in Table 2.4. Figure 2.2 is illustrated the size of typical particles in the water and wastewater, and the molecular weight cut-off of the membranes required (Macedonio et al., 2012).

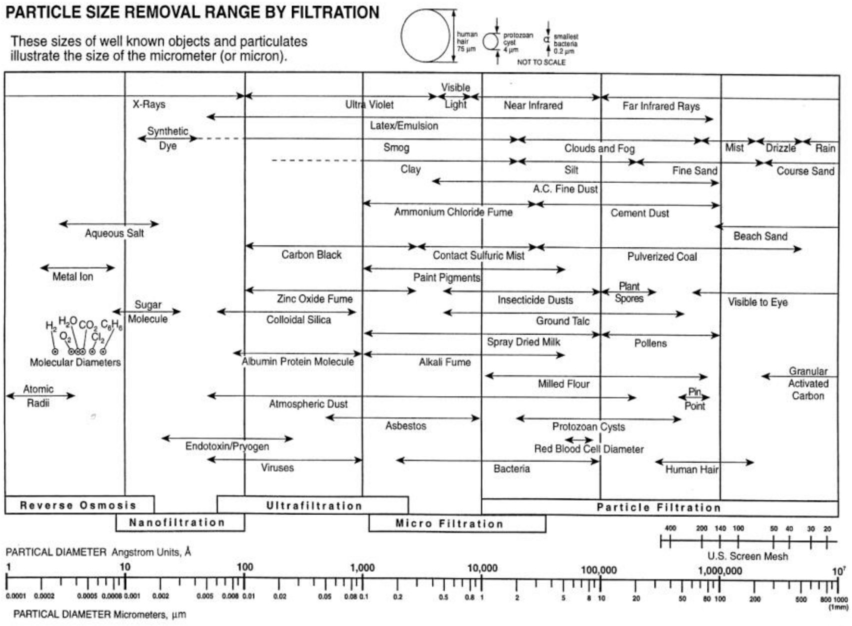


Figure 2.2 Cut-offs of different liquid filtration techniques (Macedonio et al., 2012)

Table 2.3 Summary of microfiltration (MF) (Mulder 1991)

Membranes	asymmetric porous
Thickness	10-150 µm
Pore sizes	0.05- 10 µm
Driving force	pressure (< 2 bar)
Separation principle	sieving mechanism
Membrane material	polymeric, ceramic
Main applications	analytical applications, sterilisation (food, pharmaceuticals), ultrapure water (sem1conductors), clarification (beverages), cell harvesting and membrane bioreactor (biotechnology), plasmapheresis (medical), pre-treatment, water treatment

Table 2.4 Summary of ultrafiltration (UF) (Mulder 1991)

Membranes	asymmetric porous
Thickness	150 μm (or monolithic for some ceramics)
Pore sizes	1-100 nm
Driving force	pressure (1-10 bar)
Separation principle	sieving mechanism
Membrane material	polymer (e.g. polysulfone, po1yacry1onitri1e), ceramic (e.g. zirconium oxide, aluminium oxide)
Main applications	dairy (milk, whey, cheese making), food (potato stareh and proteins), metallurgy (oil-water emulsions, electropaint recovery), textile (indigo), phannaceutical (enzymes, antibiotics, pyrogens), automotive (electro paint), water treatment

Nanofiltration (NF) is a membrane process that is used a driven-pressure (Pressures 4-20 MPa) as a function of the driving force. The sizes ranges of NF is about 1.0 μm that is between the RO and UF membrane, and the molecular cut-off is less than 1000 Da. The performance of the NF membrane is higher than the UF membrane, and it has a high rejection of divalent or multivalent ions. However, there are some a drawback of NF process that are monovalent ions can pass through the NF membrane due to the general size of divalent or multivalent ions are smaller than the NF membrane pores. Typically, NF membrane is commonly used in surface water and fresh groundwater treatment, water softening, disinfection by-product precursors such as natural organic matter and synthetic organic matter (herbicides, pharmaceuticals), and more widely used in food processing (Ecker et al., 2012, O'Grady et al., 1996, Volkov et al., 2008). Summary of nanofiltration is illustrated in Table 2.5.

Table 2.5 Summary of nanofiltration (NF) (Mulder 1991)

Membranes	composite
Thickness	sublayer (150 µm), top layer(1 µm)
Pore sizes	< 2 nm
Driving force	pressure (10-25 bar)
Separation principle	solution-diffusion
Membrane material	polyamide (interfacial polymerisation)
Main applications	desalination of brackish water, removal of micropollutents, water softening, waste water treatment, retention of dyes (textile industry)

Reverse Osmosis (RO) is unlike MF, UF, and NF processes due to the RO membranes do not have distinct pores. The main mechanism of RO process is the diffusion of water molecules through the membrane. On constancy, MF, UF, and NF have pores that are used to separate the large particles and small particles/solute by using serving mechanism. Hydraulic pressure-driven membrane, as a driving force, which is applied in the process, is higher than NF membrane (20-80 MPa). The performance of the RO membrane is highest as compared with MF, UF, and NF membranes due to it can be rejected a smallest contaminants and monovalent ions (<350 Da) from liquids by using the diffusion. The water molecules diffuse from a high concentration solution to a low concentration solution through a semi-permeable RO membrane in the presence of a high driven-pressure, which is higher than the feed water osmotic pressure. RO process is widely used in the various fields such as water improvement, water treatment, water reclamation, seawater desalination. In addition, the RO process has been widespread applied in the chemical treatment, textile, pulp and paper, petroleum and petrochemical, food, tanning and metal finishing industries, fibres and oily constituents (Ang and

Elimelech 2008, Bódalo-Santoyo et al., 2003, Vrijenhoek et al., 2001). Summary of reverse osmosis is illustrated in Table 2.6.

Table 2.6 Summary of reverse osmosis (RO) (Mulder 1991)

Membranes	Asymmetric or composite
Thickness	sublayer (150 μm), top layer(1 μm)
Pore sizes	< 2 nm
Driving force	pressure: brackish water 15-25 bar, seawater 40-80 bar
Separation principle	solution-diffusion
Membrane material	cellulose triacetate, aromatic polyamide, polyamide and poly (ether urea)
Main applications	desalination of brackish and seawater, production of ultrapure water (electronic industry), concentration of food juice and sugars (food industry), and the concentration of milk (dairy industry)

Forward Osmosis (FO) process is an innovative technology in the membrane filtration process. The water molecules diffuse form a low concentration (feed solution) to a high concentration (draw solution) though a selectively permeable membrane. The driving force of FO process is an osmotic pressure gradient between the feed solution and draw solution. In the FO process, which is the diffusion process of solutes, uses a semi-permeable membrane to separate the water from dissolved solutes. Moreover, unlike RO, which uses applied hydraulic pressure as the driving force to counteract the osmotic pressure gradient between the lower concentration and higher concentration (Cath et al., 2006b). Furthermore, osmotic driving forces in FO can be significantly greater than hydrodynamic driving forces in RO, potentially leading to higher water flux rates and recoveries (Cath et al., 2006b, McCutcheon et al., 2005). There are several researches have been reported the advantages of the FO process such as it operates at low or no hydraulic pressures, high rejection of a wide range of contaminants, may have a lower membrane fouling propensity than pressure-driven membrane processes, the equipment used is very simple (Cath et al., 2006b, Holloway et al., 2007). In addition, the FO process has been widely studied and applied in the various fields such as wastewater treatment and water purification (Kravath and Davis 1975), concentration of liquids from anaerobic sludge digestion (Holloway et al., 2007), food and pharmaceutical industry (Chung et al., 2012, Dova et al., 2007), reclaiming wastewater (Lutchmiah et al., 2014), desalinating seawater (Kravath and Davis 1975), purifying water in emergency relief situations (McCutcheon et al., 2005). Detailed information on FO process discussed in the following section;

2.2 Forward Osmosis Process

Forward Osmosis (FO) process is a new membrane technology. The water molecules in a lower concentration solution (feed solution) move to a higher concentration solution (draw solution) through a selectively permeable membrane. The osmotic pressure gradient used as a driving force of FO process is produced from the different concentration of feed solution and draw solution. In the FO process, the osmotic pressure gradient ($\Delta\pi$) is a different concentration of solution, and it related to the performance of the FO process, on constancy, RO process highly applied hydrodynamic pressure as a function of driving forces (Figure 2.3) (Cath et al., 2006b). Comparison between RO and FO systems is provided in Table 2.3. In addition, the change of the osmotic pressure gradient is caused the transport of the water molecules of the solution, then, the performance of the FO process can be reduced with the increase water molecules in the draw solution because the effective osmotic pressure across the membrane reduces. The relative of the transportation of the water molecules and the osmotic pressure gradient could be clearly seen in the Figure 2.3.

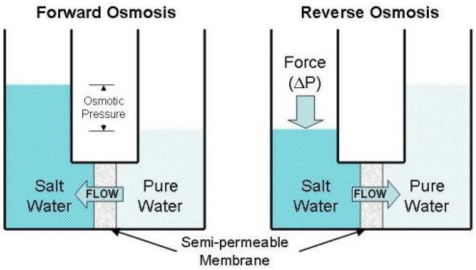


Figure 2.3 Forward Osmosis (FO) and Reverse Osmosis membrane (RO)

2.3 Draw solution of forward osmosis process

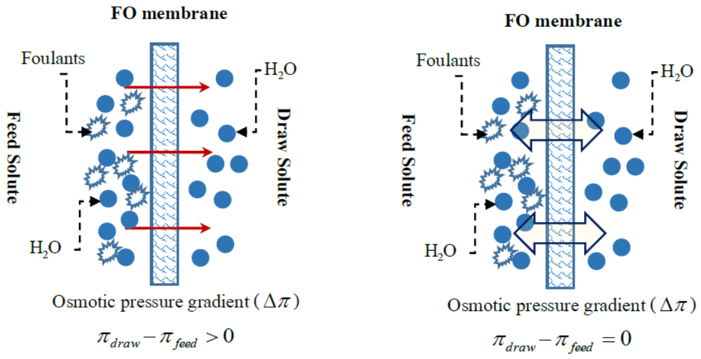
Generally, the performance of FO process based on the osmotic pressure gradient ($\Delta\pi$), therefore, the change of concentration between the feed and draw solution is interestingly essence of the FO process. While the concentration of the draw solution increases, its osmotic pressure gradient increases. The selecting a draw solution for the FO process is one of the important things. The main criterion is that it has a higher osmotic pressure than the feed solution (Cath et al., 2006b). In the FO process, the two main challenges associated with draw solutions include finding a suitable solution that provides a strong driving force for mass transport and the energy consumption associated with re-concentrating the draw solution for continuous FO operation, and the key criteria for the selection of a draw solution include (Achilli et al., 2009, Klaysom et al., 2013a). The minimum characteristic of draw solution should be:

1. Draw solution should have high osmotic pressure Reverse diffusion of the draw solutes (leakage through the membrane into the feed) should be minimal.
2. Draw solutions can be easily and economically re-concentrated and water recovered and draw solution must not be toxic.
3. Draw solution should be inexpensive.

4. Draw solution should not degrade the membranes and should not cause scaling or fouling on the membrane surface.

Table 2.7 Comparison between RO and FO process (Klaysom et al., 2013a)

Characteristics	**Reverse Osmosis (RO)**	**Forward Osmosis (FO)**
Driving force	Hydraulic pressure (P)	Osmotic pressure($\Delta\pi$)
Main application	- Water purification process - Desalination	- Water purification process - Desalination
Operating condition	- Pressure: 10-70 bar - Brackish and seawater feed Solution - pH 6-7	- Pressure: atmospheric - Brackish, seawater or some synthetic draw solutions, such as aqueous NH_3 - Impaired water, seawater or other feed solution - pH 6-11
Desirable membrane property		
- Physical morphology	- Dense top layer and porous sublayer - Good thermal and mechanical stability	- Thin membranes with dense active layer on porous, low torturous sub-layer
- Chemical property	- Good chemical stability to chloride solution	- Very hydrophilic - Good chemical stability to chloride solution
- Membrane requirement	- High water permeability - High solute retention - Robust for high pressure operation	- High water permeability - High solute retention - Stable in synthetic draw solution



(a) Osmosis process (b) Equilibrium phase

Figure 2.4 Transport of water molecules across the FO membrane.

π_{draw} = osmotic pressure of draw solution, π_{feed} = osmotic pressure of feed solution, and $\Delta\pi$ = osmotic pressure gradient

In addition, several researches have been reported the some draw solutions and the recovery methods are summarized in Table 2.8-2.10.

Table 2.8 Inorganic draw solutions and their recovery methods (Klaysom et al., 2013a)

Draw solutes	**Advantage**	**Disadvantage**	**Recovery**
- NaCl, $MgCl_2$, $NaSO_4$	- Inexpensive solute; readily available - Cheap production cost	- Difficult separation	- NF, RO, distillation
- Removable solute by pH adjustment (i.e., metal carbonates, oxalates or tartrates)	- Comparable product purity compared to RO	- High capital investment	- pH change to induce precipitation and filtration
- $Al_2(SO_4)_3$	- Inexpensive recovery - High solubility in water	- High chemical demand and large-scale process design - Toxic	- Multi-state chemical precipitation
- Thermolytic/volatile - SO_2 - NH_3-CO_2	- Re-concentration with low-grade heat	- Toxic - product, NH_3; diffusive loss	- Heated gas stripping - Heating (60 °C) results in thermolysis

Table 2.9 Organic draw solutions and their recovery methods (Klaysom et al., 2013a)

Draw solutes	Advantage	Disadvantage	Recovery
- Alcohols	- No separation necessary	- Difficult separation	- Distillation
- Glucose (and other sugars)	- High solubility in water	- Application and Low driving force	- None necessary
- Albumin	- Designable to increase	- Increasing ICP with further	- Denaturation and - solidification upon heating
- Methylimidazole based compounds - Magnesium acetate (and other organic salts)	- Carbon source	- Modification - Limited application	- FO-MD - Biodegraded in FOMBR

Table 2.10 Polymer-based draw solutions and their recovery methods (Klaysom et al., 2013a)

Draw solutes	Advantage	Disadvantage	Recovery
- Polyethylene glycol (PEG)	- Easy recovery	- Low	- UF or NF
- Cloud point solute such as fatty acids	- High driving force	- Require heating unit/temperature control	- Cloud point precipitation and filtration
- Polyacrylic acid	- High driving force through dissociation of surface group	- Increased viscosity	- UF
- Hydrogel	- High driving force through dissociation of surface groups	- Multiple-step synthesis - Low water flux	- De-swelling by heating or Pressurization

2.4 Mass transport phenomena of forward osmosis process

The mass transport of the FO process is quite complex phenomena, and depended on a various factors including type of membrane, structure, orientation, temperatures, compositions of the feed, draw solutions and hydraulics (Phillip et al., 2010). To be described the mass transport of the FO process, the diffusion of the water molecules though the FO membrane, is commonly used to be explained the mass transport of FO process (Figure 2.5). In addition, FO process typically utilizes orientation, which uses the active layer of the membrane contact with the feed solution (contaminants), and the supporting layer contact the draw solution.

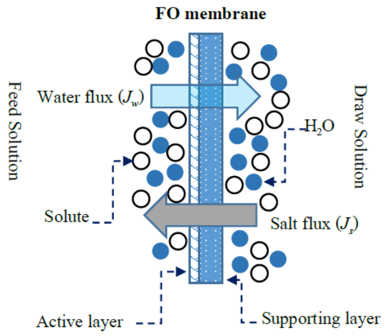


Figure 2.5 Direction of water and salt fluxes for FO process

2.4.1 Water and Solute fluxes

The transport of water and solute are typically used to explain the classical solution diffusion model. Equation (2.1) is referred to the water flux of the RO process. As reviewed, RO process highly applied hydraulic pressure as a driving force to push the water/solute diffuse though the selective permeable membrane, therefore, the hydraulic pressure would be higher than the osmotic pressure $(\Delta\rho > \Delta\pi)$. On constancy, FO process uses the osmotic pressure gradient as a main force of process, thus, the osmotic pressure gradient should be higher than the hydraulic pressure (assume $\Delta\rho = 0$). It can be written by equation 2.2.

$$J_w = A(\Delta\rho - \Delta\pi) \qquad 2.1$$

$$J_w = A(\Delta\pi - \Delta\rho) \quad 2.2$$

Where, J_W is the water flux (L/m^2h), A is the water permeability constant ($ms^{-1}Pa^{-1}$), $\Delta\pi, \Delta\rho$ is the osmotic pressure gradient and hydraulic pressure, respectively.

During the diffusion of water molecules from the feed solution to the draw solution, the salt molecules from the draw solution also diffuse through the membrane to the feed solution. It is described by the salt flux. The diffusion of the salt molecules can be referred as a function of the salt flux (J_S):

$$J_s = B(\Delta C) \quad 2.3$$

Where, B is the salt permeability coefficient (ms^{-1}), ΔC is the concentration difference across the membrane selective layer.

The salt permeability coefficient B of membranes can also be determined using equation 2.4, 2.5 and 2.6:

$$B = \frac{A(1-R)(\Delta\rho - \Delta\pi)}{R} \quad 2.4$$

Due to, $\Delta\rho = 0$

$$B = \frac{A(1-R)(\pi_{draw} - \pi_{feed})}{R} \quad 2.5$$

$$R = \frac{C_p}{C_f} \quad 2.6$$

Where, R is the salt rejection of the membrane (i.e., the fraction of salts retained in the feed solution), C_p, C_f are the salt concentration of permeate and feed solution, π_{draw}, π_{feed} are an osmotic pressure of draw and feed solution, respectively.

2.4.2 Concentration polarization

Concentration polarization is one of the mainly impact of osmotically-driven membrane process. Concentration polarization (CP) is generally appeared near the surface of the active layer. The common phenomenon of concentration polarization is the bulk osmotic pressure difference is much higher than the osmotic pressure difference (Cath et al., 2006b, Lee et al., 1981, Loeb et al., 1997, McCutcheon et al., 2006). Concentration polarization in the membrane process can be developed at the membrane-liquid interface (i.e., external concentration polarization (ECP)), and that can be developed inside the membrane support structure (i.e., internal concentration polarization (ICP)). As shown in Figure 2.6, in the immediate neighborhood of the membrane surface, the solute concentration increases on the feed solution side and decreases on the draw solution side, and this results in a reduced concentration gradient and thus a reduction in the osmotic pressure difference between the two solutions (Liu, 2013). As shown in Figure 2.6, the real driving force across an FO membrane, $\Delta\pi_m$, is lower than the osmotic pressure difference of bulk solutions, $\Delta\pi_{bulk}$. Therefore, the presence of CP inhibits permeate flow due to the decreased osmotic pressure across the membrane barrier (Liu 2013). In addition, there are two types of concentration polarization (CP) phenomena would be discussed below:

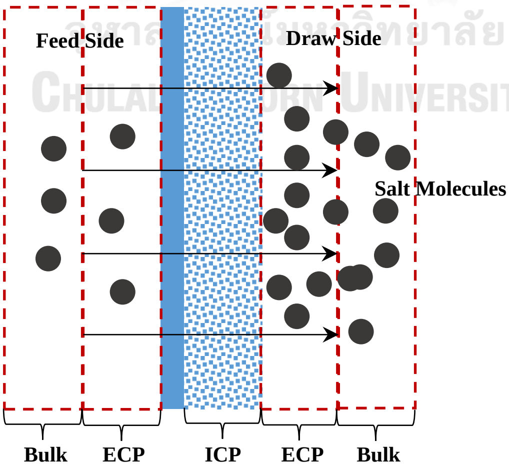


Figure 2.6 Schematic illustration of dilutive concentration polarization across an asymmetric FO membrane (Liu 2013)

2.4.3 External concentration polarization (ECP)

External concentration polarization (ECP) is one of the type of concentration polarization that is occurred outside of the membrane. In the pressure-driven membrane process (RO process), only concentrative ECP is mainly generated at the surface of the membrane active layer. However, in the FO process, the ECP can be occurred in both concentrative external concentration polarization (CECP) and dilutive external concentration polarization (DECP) (McCutcheon and Elimelech 2006). In addition, concentrative external concentration polarization (CECP) phenomena in the FO process commonly generates when the draw solution contracts with the membrane support layer, while dilutive external concentration polarization (DECP) phenomena generates when the feed solution contacts with the active layer. The interesting of ECP that decreases the net driving force due to increased osmotic pressure at the membrane active layer interface on the feed side of the membrane, or decreased osmotic pressure at the membrane active layer surface on the draw solution side (Zhao et al., 2012). Moreover, the effect of the ECP can be reduced by the increasing the flow turbulence or velocity, or optimizing the water flux (Cath et al., 2006b, Mulder 1991, Zhao et al., 2012).

McCutcheon et al., (2006) stated the intensively investigated the correlation between flux and concentration polarization. The ECP module was developed based on the boundary layer film theory.

$$\frac{\pi_{F,m}}{\pi_{F,b}} = \exp\left(\frac{J_w}{k}\right) \qquad 2.7$$

Where, $\pi_{F,b}$ is osmotic pressure of the bulk feed and draw solution (Pa), $\pi_{F,m}$ is osmotic pressure of feed and draw solution near membrane surface (Pa), D is the diffusion coefficient of the solute in draw or feed solution, d_h is the hydraulic diameter of the flow channel. *k* is the mass transfer coefficient in the flow channel,

$$k = \frac{ShD}{d_h} \tag{2.8}$$

The ratio of osmotic pressure at the membrane surface to that in the bulk solution is assumed equivalent to the ratio of concentrations. This is reasonable for relatively dilute solutions following Van't Hoff's equation. Common formulas used in calculating the Sherwood number for different flow regimes in a rectangular channel include:

$$Sh = 1.85\left(\mathrm{Re}\, Sc \frac{d_h}{L}\right)^{0.33} \tag{2.9}$$

Laminar flow; Re ≤2100;

$$Sh = 0.04\,\mathrm{Re}^{0.75}\, Sc^{0.33} \tag{2.10}$$

Turbulent flow; Re ≤2100; Where Re is the Reynolds number, *Sc* the Schmidt number, and L is the length of the flow channel.

2.4.4 Internal concentration polarization (ICP)

As reviewed, there are two types of concentration polarization of the FO process; namely, external concentration polarization and internal concentration polarization. Internal concentration polarization (ICP) is given:

$$\frac{\pi_{D,i}}{\pi_{D,b}} = \exp(-J_w k) \tag{2.11}$$

Where, $\pi_{D,i}$ is osmotic pressure of feed and draw solution near membrane surface inside porous supports (Pa), $\pi_{D,b}$ is osmotic pressure of the bulk feed and draw solution (Pa).

For simplicity, the applied hydraulic pressure is omitted in the following equations. By incorporating the correction factors, the flux equation in FO mode becomes:

$$J_w = A(\Delta\pi_{eff}) = A(\pi_{D,i} - \pi_{F,m}) \qquad 2.12$$

From equation 2.7 and 2.11,

$$J_w = A\left[\pi_{D,i}\exp(-J_w K) - \Delta\pi_{F,b}\exp(\frac{J_w}{k})\right] \qquad 2.13$$

2.5 Osmotic membrane

The developed FO membrane is interestingly issue in the osmotic-driven membrane process due to it related to the performance of solution-diffusion between the feed solution and draw solution. In the FO process, the characteristic of membrane would be reject salts and at the same time pass more water molecules at a reasonable rate (Fane 2007). Thus, the ideal characteristic of FO membrane has a high water flux, high salt rejection, resistant to biological attack, resistant to membrane fouling by suspended material, inexpensive, mechanically strong, chemically stable, able to resist high temperatures, safe operation at high pressures, easy to clean, and no internal leaks (Lay et al., 2012a, Sairam et al., 2011, Wang et al., 2010b). According to the membrane materials, the mainly composited membrane materials are the cellulose acetate (CA) and polyamides that are selected to prefer materials used for synthesis of osmotic membranes. At present, new technology is able to stable structure of membrane, and it is commonly selected to apply in various fields. There are now two commercial osmotic membranes commonly used in the osmotically-driven membrane process (Klaysom et al., 2013a). As detailed below:

Asymmetric membranes: Several researches have been studied and used the cellulose acetate (CA) in the fabrication of RO membrane due to it is highly hydrophilic properties (Cano-Odena et al., 2011, Zhang et al., 2010). The advantages of the cellulose acetate are resists fouling relatively well and can achieve good water flux (Zhang et al., 2010). In addition, CA membranes possess good resistance to chlorine and other oxidants commonly used in the pre-treatment of feed water and cleaning of the membrane (Cano-Odena et al., 2011).

Thin-film-composite membranes**:** the thin-film composite membrane is widely applied and studied for the FO process due to it is high performance and easy cleaning. There are two sides of membrane; the selective layer and the support layer are a mainly composed of the structural membrane. The advantages of thin-film composite membrane are good salt retention of the selective layer with low internal concentration polarization (ICP) in the porous support layer to enable high water flux (Klaysom et al., 2013a). In addition, the different surface can be supported the moment of the water and the solutes. The support layers are important to subsequent form a good selective skin layer at the substrate surface (Phillip et al., 2010). Typically, the polysulfone (PSf) is widely used support materials for traditional thin-film composite membrane (Su and Chung 2011). The selective skin-layers polyamide (PA) based membranes possess is the importantly structural membrane due to it can be a high flux, good salt and organic rejection, and stability under a wide range of operating conditions (Chou et al., 2010).

2.6 Characterization of membranes

The important mechanism of FO process is the diffusion of water passes though the selective permeable membrane as well as rejection of solutes and contaminants. The increased performance or the movement of water flux is generally depended on the properties of membrane (Li et al., 2007). The different membrane surface characterization methods are needed to obtain enough information on the membrane properties. The most important characteristics of membranes affecting their performance and stability in a specific application are their chemical composition, hydrophobicity, charge and morphology (McCutcheon and Elimelech 2006). In addition, the streaming potential, AFM, and contact angle measurements are mainly used for membrane surface characterization (Cath et al., 2006b, Lay et al., 2012a, Zhao et al., 2012). Thus, the change of the properties after the interaction between the membrane fouling and the membrane surface need to be investigated.

2.6.1 Characterization of membrane chemical structure

The change properties of membrane surface are needed to demonstrate for a clearly understand of membrane stability under different conditions. The further information about the covered chemistry on the membrane surface can be clearly understood the determination of fouling mechanisms and the behavior of flux decline. The change of chemical composition and structure of the membrane can be analyzed with a various methods such as Attenuated Total Reflectance Fourier transform infrared (ATR-FTIR) method, Raman spectroscopy, infrared spectroscopy (IR), X-ray Photoelectron Spectroscopy (XPS), Secondary Ion Mass Spectroscopy combined with a mass analyzer called time-of-flight (TOF-SIMS) are the most surface-sensitive methods. The characterization methods are commonly applied to demonstrate the change of membrane properties as reviewed in the Table 2.7.

2.6.2 Characterization of membrane charge

The electrical characteristic of membrane surface is one of important essence of the membrane process. The membrane charge can be analyzed based on known membrane chemical structure and compositions. Several methods can be applied to monitor the characterization of the electrical properties of the membrane surface. Furthermore, the zeta potential method is widespread applied in the charge measurement of solution and membrane surface. The zeta potential values will be given the information of membrane surface charge due to the change of membrane is involved the movement of water molecules and solute. More negatively charged of membrane surface increased the movement of water molecules, in other words, the performance will be increased. Therefore, the affecting of interaction of membrane fouling in the raw water or wastewater and the membrane surface is demonstrated by the zeta potential measurements.

Table 2.11 Characterization methods for clean membranes (Klaysom et al., 2013a)

<table>
<tr><th colspan="4">Characterization Technique</th><th>Parameter</th></tr>
<tr><td rowspan="2">Chemical structure characterization</td><td colspan="3">Spectroscopy</td><td>IR(ATR-FTIR),
Raman spectroscopy,
XPS (or ESCA), SIMS</td></tr>
<tr><td>Membrane resistance</td><td colspan="2">Permeability</td><td>Chemical composition,
Polymer morphology</td></tr>
<tr><td rowspan="3">Functional characterization</td><td colspan="3">Selectivity</td><td rowspan="3">Charge density,
zeta potential</td></tr>
<tr><td colspan="3">Contact angle measurement</td></tr>
<tr><td colspan="3">Electrokinetic measurements (MP, TSP, SP, Titration)</td></tr>
<tr><td>Hydrophilicity/hydrophobicity</td><td colspan="3">Electrochemical impedance spectroscopy (EIS)</td><td>Ion conductivity in the pore</td></tr>
<tr><td rowspan="2">Electrical characterization</td><td colspan="3">Microscopy</td><td>Optical microscopy</td></tr>
<tr><td colspan="3">Microscopy</td><td>CSLM</td></tr>
<tr><td rowspan="2">Morphological characterization</td><td colspan="2" rowspan="2">Microscopy</td><td>SEM</td><td>macrostructure</td></tr>
<tr><td>AFM</td><td>Top-layer and pore size distribution</td></tr>
</table>

2.7 Membrane fouling

Membrane fouling is the main key issue all membrane separation processes. It affects the separation efficiency and water productivity of the whole treatment system. Thus, it is necessary to effectively control or minimize the development of membrane fouling layer on the membrane surface. In the pressure-driven membrane process (UF, MF); the membrane fouling is mainly causing of flux decline due to the membrane fouling confine the movement of water molecules. In contrast, membrane fouling is enhanced the osmotic pressure in the feed solution of osmotically-driven membrane process. More deposited membrane fouling on the surface can reduce the movement of the water molecules form a feed solution to draw solution, causing the low permeate production and increase of transmembrane pressure. Membrane fouling is influenced by three major factors: the membrane material properties (e.g. hydrophilicity, roughness, and electrical charge), the feed solution characteristics (e.g. the nature and concentration of the foulant) and the operating conditions (Cath et al., 2006b). The interactions between the membrane surface and the foulants are interestingly essence need to be demonstrated. According to the type of foulants, the corresponding fouling in wastewater treatment and reclamation can be generally classified into organic, inorganic, biological and colloidal fouling (Amy and Cho 1999, Ang et al., 2011, Li et al., 2007).

Organic Fouling-Effluent Organic Matters (EfOM), which are considered as major organic foulants have been investigated intensively (Jarusutthirak et al., 2002, Jarusutthirak and Amy 2006, Shon et al., 2004). Generally, EfOM in wastewater effluents originate from three different sources: natural organic matters (NOM) present in the drinking water, synthetic organic compounds discharged by consumers and disinfection by-products generated during disinfection processes, and soluble microbial products generated during biological wastewater treatment. Typical organic constituents in treated domestic wastewater and their size ranges are shown in Figure 2.7. Although NOM in drinking water (surface water as a source) attributes to fouling in low pressure membrane filtration (Hallé et al., 2009, Huang et al., 2007, Kennedy et al., 2008), recent evidences have shown that the EfOM foulants in membrane filtration of treated domestic wastewater are different to NOM foulants in drinking water. Furthermore, the high molecular organic compounds demonstrate much more severe fouling effect than other organic fractions. This result coincides with the result reported by previous studies (Jarusutthirak et al., 2002). Mostly SMP and/or extracellular polymeric substances (EPS) which are mainly formed during biological wastewater treatment processes (Jarusutthirak et al., 2002).

SMP is defined as the pool of organic compounds that result from substrate metabolism (usually with biomass growth) and biomass decay during the complete mineralization of simple substrates (Barker and Stuckey 1999). This definition concerns soluble cellular components in relation to different activities of microorganisms e.g. excreted by microorganisms due to their interaction with the environment, produced of substrate metabolism and bacteria growth or released during the lysis and degradation of microorganisms (Chou et al., 2010). Some of SMP have been identified as humic and fulvic acid, polysaccharides, proteins, nucleic acids, amino acids, structural components of cells and products of energy metabolism (Jarusutthirak and Amy 2006).

EPS is used as a general term which encompasses all classes of autochthonous macromolecules such as carbohydrates, proteins, nucleic acids, phosphorous lipids and other polymeric compounds found at or outside the cell surface and in the intercellular space of microbial aggregates (Flemming and Wingender 2001).

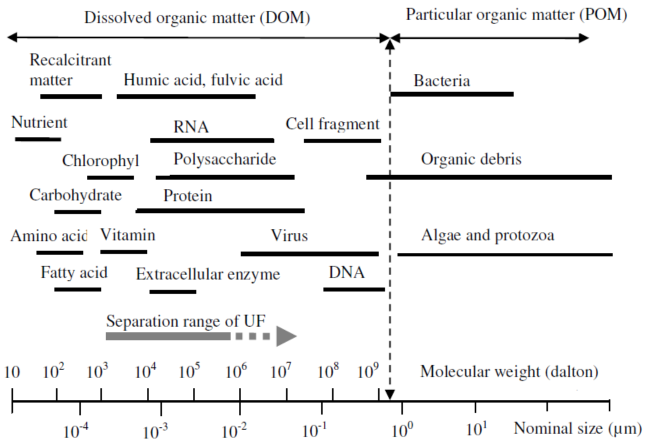


Figure 2.7 Typical organic constituents in biological treated domestic wastewater (Adapted from Levine et al., 1985)

Biofouling: Biofouling is defined as the undesired development of microbial layers (biofilms) on membrane surfaces (Li et al., 2007). Biofilm is an expression, which applies to microbial life in aggregates combined through EPS which contains mainly polysaccharides and proteins (Flemming and Wingender 2001). Generally, biofouling mechanisms in membrane processes include the adsorption of soluble and suspended EPS on membrane surfaces and in membrane pores, the clogging of the membrane pore structure of fine colloidal particles and cell debris, and the adhesion and deposition of sludge cake on membrane surfaces(Liao et al., 2004). As bacteria alone cannot foul the membrane seriously, the far more important foulants are the EPS secreted from them (Xu and Chellam 2005). Due to the accumulation of EPS and their reaction with solute ions, mass transfer coefficient in the water phase can be reduced and this contributes significantly to permeate flux decline in membrane filtration (Kim et al., 2006). Moreover, the secreted EPS decrease the effectiveness of backwashing and lead to irreversible fouling (Xu et al., 2006). The EPS gel structure protects also bacterial cells from hydraulic shearing and from chemical attack of biocides such as chlorine (Li et al., 2007). Based on the characteristics of the active substances in biofouling, the classification of biofouling is overlapping within organic fouling. Biofouling can then be considered as a biotic form of organic fouling (Amy and Cho 1999). The severity of biofouling in wastewater reclamation is greatly related to the characteristics of the feed water, such as nutrient availability, turbulence, temperature, particles, etc. The structure of microbial community and the surface condition of the membrane surface influence the process also to some degree (Ahmed et al., 2007, Melo and Bott 1997).

Inorganic Fouling: Inorganic fouling is caused by the accumulation of inorganic precipitates (such as metal hydroxides and carbonates) and scales on membrane surfaces or within the pore structure (Li et al., 2007). Precipitates are formed when the concentration of these chemical species exceed their saturation concentrations, which is a major concern for RO and NF as they reject most of the solved inorganic species. For UF and MF, inorganic fouling due to concentration polarization is much less profound, but can exist most likely due to interactions between ions and other fouling materials, e.g. organic foulants via chemical bonding (Costa et al., 2006, Liang et al., 2008). If pre-treatment processes for membrane filtration such as coagulation or oxidation are not designed or operated properly, it may introduce metal hydroxides into fouling matrix (Zhao et al., 2012). Inorganic fouling/scaling can be a significant problem for make-up water of caustic solutions prepared for chemically enhanced backwash or chemical cleaning (Lin et al., 2010).

2.8 Surfactants

2.8.1 Definition of surfactants

Surfactant is an abbreviation for surface-active agent, which literally means active at a surface. The molecular structure of surfactants is amphiphilic, consisting of both non-polar (hydrophobic, or tail) and polar (hydrophilic, or head) parts, as shown in Figure 2.8. When dissolved in a solvent, surfactants tend to adsorb (or locate) at interfaces, with hydrophilic head retaining in the polar phase while the hydrophobic tail facing the apolar phase, thereby altering significantly the physical properties of those interfaces. The driving force for a surfactant to adsorb at an interface is to lower the free energy of that phase boundary (Holmberg et al., 2002).

Nowadays, synthetic surfactants are essential components in many industrial processes and formulations, such as household detergents, personal care formulations, industrial and institutional washing and cleaning, as well as numerous technical applications such as textile auxiliaries, leather chemicals, agrochemicals (pesticide formulations), metal and mining industry, plastic industry, lubricants, paints, polymers, pharmaceutical, oil recovery, pulp and paper industry (Lin et al., 2010, Mai 2013, Renner 1997).

2.8.2 Structure and classification

As previously reviewed, the head of surfactant is used to divide the types of surfactants as well as the structure and the composition of the surfactant can be classified the type of the surfactant. The hydrophobic group of the surfactant structure is usually a single or double straight or branched hydrocarbon chain, but may also be a fluorocarbon, or a halogenated or oxygenated hydrocarbon or siloxane chain (Mai 2013). Surfactants are classified by the polar head group, and depending on the nature of the hydrophilic head group, surfactants are therefore classified into four basic types: anionic, cationic, non-ionic and zwitterionic surfactants.

Anionic surfactants are those molecules of which the surface-active portion bears a negative charge. Common anionic surfactants are sulfonic acid salts, sulfuric acid ester salts, carboxylic acid salts, phosphoric and polyphosphoric acid esters, and perfluorocarboxylic acids.

Cationics contain a hydrophilic group positively charged, for example, long-chain amines and their salts, acylated diamines and polyamines and their salts, quaternary ammonium salts.

Nonionics bear no appearent ionic charge in their hydrophilic part, which include a high polar (non-charged) moiety, such as monoglyceride of long-chain fatty acid, poly-oxyethylenated alkylphenol, poly-oxyethylenated alcohol.

Zwitterionics (or amphoterics) carry both positive and negative charges in the head group. Long-chain amino acid and sulfobetaine are the most encounted examples of this type of surfactants.

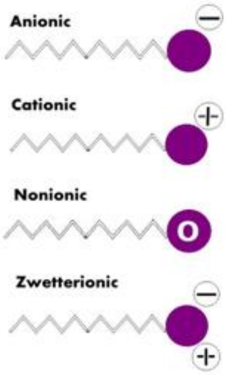


Figure 2.8 Amphiphilic structure of surfactants. The head corresponds to the hydrophilic part of the surfactant molecule, which is polar, while the tail represents the hydrophobic group of the surfactant molecule, which is apolar.

Critical micelle concentration (CMC) is the concentration below which virtually no micelles are detected and above which virtually all additional surfactant molecules form micelles. In addition, aggregation number is the number of surfactant molecules present in a micelle once the CMC has been reached.

2.8.3 Surfactant adsorption at solid-liquid interface (Mai 2013)

The adsorption of surfactants can be strong tendency to adsorb at interfaces in an oriented way. The mechanism of adsorption of surfactants at the solid-liquid interface is strongly influenced by several factors (Mai 2013, Zhang and Somasundaran 2006). However, the adsorption of the surfactant onto the solids can be described as below:

1. The nature of the structural groups on the solid surface: the charged sites or essentially nonpolar groupings and the constitution (e.g. the atoms and functional groups) of these sites or groupings;
2. The molecular structure of the surfactant being adsorbed: the charge of the hydrophilic part, and the structure of the hydrophobic tail group (i.e. length of the straight or branched chain, aliphatic or aromatic hydrocarbons) of the surfactant molecule;

3. The chemical and physical conditions of the aqueous solution: the pH, temperature, the presence of any electrolytes or other additives (alcohol, urea, etc);

2.8.4 Mechanisms of surfactant adsorption at solid-liquid interface (Mai 2013)

The mechanisms by which surfactants may adsorb onto solid surfaces from aqueous solutions are determined together by the factors as listed above. Several mechanisms are briefly described as follows:

1. Ion exchange between surfactant ions and similarly charged counter-ions adsorbed onto the solid surface from the solution;
2. Ion pairing of surfactant ions from solution onto oppositely charged sites of the solid surface, which has been occupied by counter-ions;
3. Acid-base interaction via either Lewis acid-base reaction, or hydrogen bonding between surfactant molecules and the solid surface;
4. Attraction by polarization of π electrons; this may occur if the solid surface contains strongly positive sites and there are electron-rich aromatic nuclei in the surfactant molecule;
5. $\pi - \pi$ interaction between aromatic nuclei of the surfactant molecule and of the solid surface if both contain such function group;
6. Adsorption by *London-van der Waals* dispersion forces between surfactant and solid surface molecules;
7. Hydrophobic bonding between tail groups of the surfactant molecules drives them to escape from water and onto the solid surface, while hydrophobic bonding between the tail-groups of the surfactant molecules and hydrophobic sites on the solid surface;

In aqueous systems, the structures formed are determined by the interaction of the surfactant molecules with the solid surface in order to minimize exposure of the hydrophobic groups to water (Warr 2000, Wilf and Alt 2000, Zhang and Somasundaran 2006). The composition of active layer of FO membrane surface is polyamide. Therefore, the probable interactions between the membrane surface and the surfactant molecules could be (Holmberg et al., 2002):

1. Electrostatic interactions: the carboxylic acid (-COOH) and free amine (-NH_2) groups that are not engaged in the cross-linking of the amide bond may be ionized when in contact with a surfactant solution, carrying a negative or positive charge, thus they are possible to interact with the ionic surfactants through electrostatic forces.

2. Hydrogen bonding: this may occur in the carboxylic acid (-COOH) and free amine (-NH_2) groups with the surfactants.
3. Hydrophobic interactions between surfactants and the hydrophobic sites on the membrane surface.
4. Mutual attraction (via hydrophobic bonding) of surfactant molecules with those adsorbed onto the membrane.
5. London-van der Waal forces by the amide bond.
6. Lewis acid-base interactions: this may occur in the carboxylic acid (-COOH) and free amine (-NH_2) groups.

2.8.5 Adsorption isotherms at solid-liquid interface (Mai 2013)

The adsorption is one of mechanism that is occurred during the membrane filtration. The membrane fouling in water/or wastewater move into the reactor, then, generated foulants on the membrane surface. The adsorption isotherm is related to the concentration or amount of adsorbate on the solid surface to its equilibrium concentration in the liquid phase. It is usually used to describe the surfactant adsorption at the liquid-solid interface. The information on the solid surface, such as the area covered by surfactant and the maximum surfactant adsorption can be measured. The most frequently used models for the adsorption isotherm is linear adsorption isotherm, Langmuir and Freundlich adsorption isotherm.

Linear adsorption isotherm

The linear adsorption isotherm formally resembles Henry's law, so it is also called Henry's adsorption isotherm. In this model, the amount of the adsorbate onto solid surface is directly proportional to its concentration in solution.

$$q_{ads} = K_H C_{eq} \tag{2.23}$$

Where; q_{ads} is the amount of surfactant adsorption onto the adsorbent, mol/m^2 or g/m^2. K_H is the Henry adsorption constant, L/m^2. C_{eq} is the equilibrium concentration of the surfactant in solution, mol/L

Typically, the linear isotherm can be used to describe the initial part of many practical isotherms for low concentrations/surface coverage or very low interaction energy between the adsorbate and the adsorbent.

Langmuir adsorption isotherm

Langmuir adsorption isotherm model is commonly applied to the surfactant adsorption from aqueous solutions, expressed by (Zhang and Somasundaran 2006):

$$q_{ads} = \frac{q_m c}{c + 1/K_L} \tag{2.24}$$

Where; q_{ads} is the surface concentration of the surfactant per unit area (or per unit mass) of the solid adsorbent, in mol/m^2 (or mol/g), at monolayer adsorption. C is the concentration of the surfactant in the liquid phase at adsorption equilibrium in mol/L. K_L is the Langmuir constant, in L/mol, containing information related to the adsorbate-adsorbent interaction free energy in the system. $1/K_L$ is 55.3 exp (ΔG^0 /RT), at absolute temperature T, in the vicinity of room temperature and where ΔG^0 is free energy of adsorption at infinite dilution.

The application of Langmuir model is valid in theory only when the following restrictions are met: (1) the solid surface is homogeneous consisting of adsorption sites; (2) all adsorbed surfactants interact only with one site and not with each other; (3) the adsorption film is monomolecular. This model also has been very useful for studying adsorption systems between surfactants and polymeric materials.

The adsorption of nonionic surfactants onto UF membranes during filtration to the following Langmuir model (Zhang and Somasundaran 2006):

$$q_{ads} = \frac{q_{ad,\max} K_L C_{eq}}{K_L C_{eq} + 1} \qquad 2.25$$

Where; C_{eq} is the concentration of the surfactant in the liquid phase at adsorption equilibrium in mol/L. $q_{\mathrm{ad,}}$max is maximum adsorption of the surfactant per unit mass of the UF membranes, in mol/m^2 at monolayer adsorption. K_{L} is the Langmuir constant, in L/mol, containing information related to the adsorbate-adsorbent interaction free energy in the system.

S type adsorption isotherm

Due to attractive lateral interactions between surfactant molecules, the Langmuir isotherm may become S-shaped or stepped (Tabor et al., 2010). A two-step adsorption mechanism has been proposed: in the first step, the surfactant molecules are adsorbed as individual molecules or ions; then in the second step, there is a sharp increase in the adsorption as surface aggregates form through interaction of the hydrophobic chains among the surfactant molecules.

$$q_{ads} = \frac{q_\infty K_s C^{ns}}{K_s C^{ns} + 1} \qquad 2.26$$

From equation 2.26;

$$\log[q_{ads}/(q_\infty - q_{ads})] = \log K_s + n_s \log C \qquad 2.27$$

Where; q_∞ is the limiting surfactant adsorption at high concentration C. K_{S} is the equilibrium constant of the surface aggregation process. n_{s} is the average aggregation number of the surface aggregate as a general adsorption isotherm. The values of K_S and n_s could be obtained from a plot of log [q_{ads} / (q_∞ - q_{ads})] versus log$C$ if there is a linear relationship between them. If $n_s > 1$, this means surfactant aggregation at the solid surface occurs.

The adsorption isotherm of an ionic surfactant on an oppositely charged solid surface usually follows a more complicated mechanism. This typical adsorption isotherm can be subdivided into four regions when plotted on a log-log scale (Figure 2.9 and 2.10).

I phase: The surfactants adsorb as individual molecules on single surface sites at low concentrations. The amount of adsorbed surfactants is very low and the interaction between adsorbed surfactants is negligible, thus this first region is governed by Henry’s law.

II phase: It shows a sudden increase of adsorption due to the formation of primary aggregates, known as hemimicelles, when the critical aggregation concentration (CAC) is reached.

III phase: The solid surface is neutralized by the adsorbed surfactant ions, the electrostatic attraction is no longer operative and adsorption takes place due to lateral attraction alone with a weaker increasing up to a plateau region with constant adsorbed amount.

IV phase: The plateau indicates that the surfactant monomer activity becomes constant and any further increase in concentration contributes only to the micellization in solution and it does not change the adsorption quantity. In some cases, the fourth region can contain a weak maximum before arriving at the plateau.

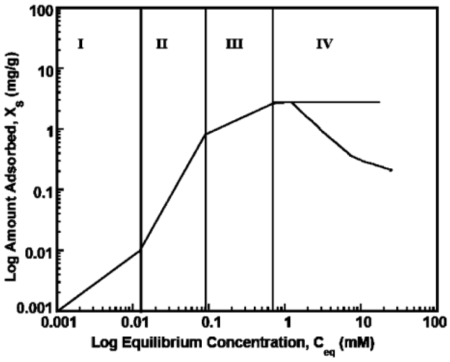


Figure 2.9 Schematic presentation of typical four-regime adsorption isotherm (Kaya et al., 2006)

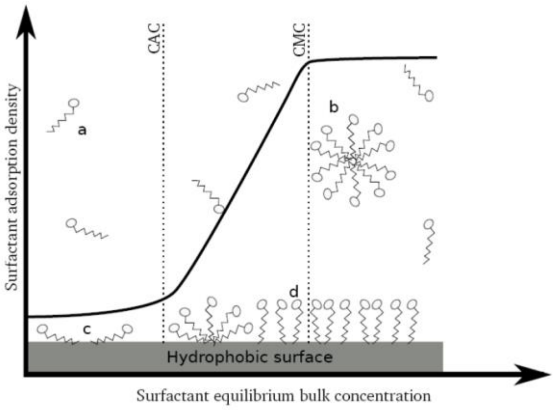


Figure 2.10 Adsorption of surfactants on hydrophobic surface. a: surfactant monomers; b: surfactant micelles; c: isolated adsorbed surfactant monomers; d: surface aggregates (Mai 2013)

Freundlich adsorption isotherm

The Freundlich equation is an empirical expression with the assumption that the adsorbent has a heterogeneous surface composed of adsorption sites with varying energy. It represents the amount of a solute on the adsorbent, to the concentration of the solute in the liquid phase at different solution concentrations. This equation is expressed as follows:

$$q_{ads} = K_f C_{eq}^{\frac{1}{n_f}} \qquad 2.28$$

Where; q_{ads} is the amount of particle adsorption onto the adsorbent, mol/m^2 or g/m^2. K_f and n_f are empirical constants for a given adsorbate and adsorbent pair at a particular temperature, with n_f generally greater than unity. C_{eq} is the equilibrium concentration of the adsorbate in solution, mol/L.

Even though this model does not describe clearly the physical phenomenon, it can be applied to the case with a heterogeneous surface where there are different adsorption sites for attachment of the solute. Since the adsorbent would not be saturated by the adsorbate in this model, the infinite surface coverage indicates multilayer sorption of the surface. Freundlich isotherm could be rewritten to the logarithmic form and a linear relationship could be obtained as follows:

$$\log q_{ads} = \log K_f + \frac{1}{n_f} \log C_{eq} \tag{2.29}$$

2.9 Membrane filtration of surfactants

Typically, surfactants are usually present in the effluent of domestic wastewater treatment plant, food engineering discharged effluents and cleaning solutions for membrane stacks used in water treatment (Ghaemi et al., 2012). Those substances are examples of highly stable organic pollutants. Their persistence to the environment has been demonstrated and, many times, the symptoms of contamination may not manifest themselves until several generations after initial contact with the chemical of concern (Purkait et al., 2004). Surfactants have been extensively used in membrane separation processes, such as pre-treatment process with surfactant solutions, removal of low molecular weight organic toxic compounds and metal ions from solutions by micellar-enhanced ultrafiltration (MEUF) (Revchuk and Suffet 2009). Removal of surfactants and estimation of interactions at surfactant membrane interface have also been studied. The surfactant micelles are retained by the membrane while monomers are too small and pass through the membrane. Membrane fouling during filtration of surfactant solutions has been studied mainly in the case of UF. In general, surfactants may cause severe fouling problems and thus decrease the membrane flux. The reason for the flux decline in some cases has been due to concentration polarization caused by retained micelles. Another reason for the decrease of permeate flux has been attributed to adsorption of surfactant molecules in the membrane surfaces through hydrophobic and/or electrostatic interactions.

Table 2.12 Membrane filtration of surfactants in literature: ultrafiltration (UF)

Membrane	Surfactant	Operating condition	Interesting results	Reference
UF - 10 kDa - Poly tetrafluoroethylene (PTFE) - Polyethersulfone (PES) - Polyamide (PA)	- Marlophen NP5 - Molecular weight: 441 g/mol - Density is 1.03 g/mL	- Stirrer speed : 200 min^{-1} - Temperature: 20 °C - Nitrogen pressure Δp : 3 bar	- Adsorption of surfactants onto the membrane surface seems to be irreversible when oil (long-chain olefin) is the continuous phase - Above the cmc, the reverse micelle formation leads to a high flux recovery.	(Nguyen et al., 2013)
UF - Polysulphone (PS) - Poly (vinylidene fluoride) (PVDF) - Cellulose acetate (CA)	- SDBS:sodiumdodecyl benzenesulphonate	- pH 1-13 - Temperature: 25 °C - Pressure Δp : 0.5 MPa	- Flux reductions of the hydrophobicmembranes were found to be much more pronounced than the flux variations of the hydrophilic membranes	(Jönsson and Jönsson 1991)
UF - Pellicon XL - Cut-off (MWCO): 10KDa	- SDS - SDBS - Tergitol NP series - Tween 80	- Temperature: 20 °C - Pressure: 0.2, 1.0 MPa	- Anionic surfactants, the permeate concentration decreased as salts concentration increased - Higher viscosity and lower water solubility caused the decrease of flux.	(Yang et al., 2005)
UF - Polyethersulfone (PES) - Cut-off (MWCO): 30 kDa	- Eumulgin ES(C_{12}/C_{14}PEO$_5$PPO$_5$)	- Cross-flow velocity: 450 ml/min. - Pressure : 0.2–0.25 MPa - Temperature: 6 - 35 °C	- The adsorption of Eumulgin ES to hydrophobic polystyrene beads leads to high loading capacities - Removing the surfactant with the permeate with a total surfactant removal of >98.8%.	(Fischer and Franzreb 2013)

Table 2.13 Membrane filtration of surfactants in literature: nanofiltration (NF)

Membrane	Surfactant	Operating condition	Interesting results	Reference
NF - Uwatech 3DTA	- Chemipur CL80	- Pressure: 20-40 bar - Temperature: 20-40 °C	- Increase of both pressure and temperature increased the flux, but the impact of pressure was higher than that of temperature. - The ideal parameters for the best retention and a reasonable flux were found to be 20°C and 30 bar and for the minimal fouling were 30°C and 30 bar.	(Kertész et al., 2008a)
NF - Cellulose acetate:100,000 Da. - Polyvinylpirrolidone (PVP): 25,000 Da	- CTAB [$CH_3(CH_2)_{15}N$ $(CH3)_3Br$] - Triton X-100 [$C_{14}H_{22}O$ $(C_2H_4O)n$ (n = 9–10))	- Temperature 25 ± 2 °C - Pressure: 4.5x10^5 Pa	- Addition of surfactants as additive resulted in membranes with superior pure water flux, permeation and rejection in comparison to CA membrane	(Ghaemi et al., 2012)
NF - Desal 51HL - NF 270 - NTR 7450 - NFPES10	- Neodol - SDBS - cetrimide	- Pressure: 8 bar - Temperature: 20 °C - pH : 6 - Cross-flow: 4.5 ms^{-1}	- The flux decline is related to the adsorbed amount of surfactants. - -The adsorption of surfactants is determined by the hydrophobic and/or electrostatic (in the case of ionic surfactants) interactions with the membrane. Hydrophilic membranes have less surfactant adsorption amount than hydrophobic ones.	(Boussu et al., 2007)

Table 2.14 Membrane filtration of surfactants in literature: reverse osmosis (RO)

Membrane	Surfactant	Operating condition	Interesting results	Reference
RO - -Polyamide composite membrane - -Thin film composite polyamide - -Cellulose acetate	- Disponils SOS 842 - Tegotenss AM VSF - Simulsols SL8 - Fluorinated surfactant	- Cross-velocity: 0.1-0.5 ms^{-1}	- The flux decline observed during reverse osmosis was governed by the adsorption of surfactants - The fouling was successfully described by a combination of the resistance-in-series and Langmuir adsorption models.	(Baudequin et al., 2014b)
RO - Thin-film composite polyamide (FT-30) - -Asymmetric cellulose acetate (CG)	- Sodium dodecyl sulfate	- Pressure:5 – 40 bar, - pH = 3 – 9, - T = 20 °C, - v = 0.9 L min^{-1}	- The surfactants were found to readily adsorb to the membrane surface - The negatively-charged sulfate functional groups of the surfactant molecules cause the membrane to become more negatively charged	(Childress and Deshmukh 1998)
RO - - Thin-film poly amide	- Fluorinated surfactant	- Pressure: 20 bar, - T = 25 °C, - v = 0.084 ms^{-1} - pH = 6.8, 7.5,8.2	- The permeate concentrations down to 10-16 g L^{-1} of fluorinated surfactant at the laboratory scale - Flux permeability decreased with increasing the surfactant concentration.	(Baudequin et al., 2011)

2.10 Chemical cleaning of surfactant

Membrane fouling is one of mainly cause of flux decline in forward osmosis. Typically, wastewater and water generally contain the membrane fouling such as biofouling, organic fouling, and inorganic fouling. Membrane cleaning is one of the methods adopted to alleviate membrane fouling and is always employed in practice. There are currently two types of cleaning method being used as physical cleaning and chemical cleaning. During the filtration, the organic fouling is strengthened and accelerated by the various interactions, more effective counter measures are necessary to reduce the interactions between fouling and membrane surface. Membrane chemical cleaning occurs through chemical reactions between cleaning chemicals and membranes or organic foulants to remove the fouling layer partially or completely (Mi and Elimelech 2010).

Cleaning agents should have some characteristics such as chemical stability, safety, low cost and ability to be washed/removed with water. The cleaning agents must be able to dissolve most of the precipitated materials and remove them from the surface of membrane with no surface damage. The chemicals should loosen and dissolve the foulants, keep the foulant in dispersion and solution form, avoid new fouling, and not attack the membrane (Wang et al., 2010a). General, chemical cleaning can be broadly classified based on cleaning agents: acids (citric acid, HCl), alkaline (NaOH), chelating agents (EDTA, polyacrylates) (Kuzmenko et al., 2005). Alkaline solutions clean organic-fouled membranes by hydrolysis and solubilization. Alkaline solutions also increase the solution pH and, therefore, increase the negative charges and solubility of the organic foulant. Metal chelating agents, such as EDTA, remove divalent cations from the complexed organic molecules and improve the cleaning of the fouled membrane. NaCl and other common inert salts can be used as an effective alternative for cleaning RO membranes fouled by gel-forming hydrophilic organic foulants.

Therefore, a successful cleaning operation is judged by not only the flux recovery but also the performance of subsequent operation to facilitate having a long membrane life-span and high operation efficiency of the membrane system. In order to achieve the best cleaning performance, most of the cleaning studies were conducted under extreme conditions, such as high pH (higher than what a membrane can typically bear) (Ang et al., 2011) . As a result, the findings of these cleaning studies may not be useful for long-term operation of a membrane. Therefore, it is essential that a membrane cleaning studies should: (i) choose a typical range of conditions (chemical types, concentration, and pH) for evaluating the cleaning performance; and (ii) adjust physical variables to relieve the stress on the membrane system induced by extreme chemical conditions. The above discussion clearly indicate the needs for conducting further research on membrane cleaning with the aim of obtaining a better understanding on cleaning mechanism and to formulate effective cleaning agent and cleaning protocol.

Table 2.15 Cleaning process in the membrane filtration (APHA et al., 2005)

Membrane	Chemical	Operating condition	Interesting results	References
NF (NF270) Feed: bacteria	- NaOH at pH 11 - 0.1 mg/l NaOCl	- Cross flow=0.5 ml/min	- Cleaning agents such as sodium dodecyl sulfate and sodium hydroxide did not effectively remove biofilms adhered to either membrane surface. - The adhesive bonds formed between the bacterial exo-polymers and membrane surfaces were only broken and the membranes effectively cleaned when sodium hypochlorite was applied.	(Cath et al., 2006b)
RO Feed: wastewater	- HC1, HNO_3 H_2SO_4, H_3PO_4, $C_6H_8O_7$, HO-SO_2NH_2 - NaOH, KOH, NH_4OH, NH_4Cl - EDTA	- Velocity=0.45 m/s - Temperature: 25 °C	- Efficiency depends on the type of the cleaning agent and its concentration. - The efficiency increases with increasing the concentration of the cleaning agent. - Operating conditions such as crossflow velocity, turbulence in the vicinity of the membrane surface, temperature, pH and cleaning time also play a role in the cleaning process.	(Klaysom et al., 2013b)
RO (FT-30) Feed: -organic and inorganic	- acids (HCl, HNO_3, H_2SO_4) - base (NaOH) - complexing agent (EDTA) - Combination	- Constant pressure = 15 bar - Cross-flow velocity= 1 m/s - Temperature = 25±2 °C	- The acids were not effective in recovering the flux. - However, the two stages of caustic and detergent. - Cleaning agents such as NaOH followed by acidic agent such as HCl provided high effective membrane regeneration.	(Lee et al., 2005)

Table 2.15 Cleaning process in the membrane filtration (continued)

Membrane	Chemical	Operating condition	Interesting results	References
RO Feed: mixture organic foulants	- NaOH - EDTA - SDS - NaCl	- Crossflow velocity = 8.6 cm/s. - Operation time = 8 h. - Initial flux = 83.0 Lm^{-2} h^{-1}	- Alkaline solution (NaOH) alone is not effective in disrupting the complexes formed by the organic foulants with calcium, a higher solution pH can lead to effective cleaning if sufficient hydrodynamic shear. - A strong chelating agent (EDTA), and salt solution (NaCl) were effective in cleaning RO membranes fouled by a mixture of foulants, especially if applied at high pH and for longer cleaning times.	(Valladares Linares et al., 2011)
FO (CTA) Feed: real wastewater Draw: NaCl	- 1%Alconoxþ0.8% EDTA mixture - 0.2%NaOH(w/v) - 0.1%NaOH - 0.5% HCl(v/v) - 2% citric acid (v/v)	- Cross- flow velocities = 2,10,and20cm/s - Draw solution of 2 mol/L NaCl - Operation time = 2, 4, 12, 24, 48, 72, 96 and 144 h	- Alkaline soaking led to a slight increase in the relative water and solute fluxes. - Acid exposure led to a decrease in these fluxes. - The changes in membrane properties caused by Alconox exposure were irreversible. - 0.1% NaOH cleaning followed by acid cleaning with either 2% citric acid or 0.5% HCl was the most effective cleaning strategy.	(Boo et al., 2012)

As previously reviewed, the forward osmosis (FO) process is widely applied in the membrane filtration (water treatment, wastewater treatment, pharmaceutical process) and has a many advantages as compared with others. There are interestingly prominent points of forward osmosis that is low energy to support the system, easy to operate and the special strongpoint is low membrane fouling. Membrane fouling is a main drawback in the membrane filtration. Several researches have been reported that the membrane fouling can reduce the performance of membrane filtration. In addition, it is a main influence in the ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). Therefore, the effect of the membrane fouling is much more interesting factor of membrane technologies.

Surfactants are generally used as substrate of detergents products such as washing chemical, detergents products, textile industrial, cleaning chemical. There are two main types of surfactants, which usually use as a substrate in the industry that are anionic surfactants and non-ionic surfactants. After using, the surfactants are continually discharged into the environmental system. Surfactants fouling are one of the interesting membrane fouling in the membrane filtration. Due to the surfactants can decrease the performance of ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) as previously reviewed. Furthermore, the main mechanism of decrease of performance is adsorption of surfactants molecules on the membrane surface. However, the effect of surfactants molecules is a few investigation in the forward osmosis (FO), including, the interaction between the surfactants molecules and the properties of membrane surface need to be more investigated. Thus, the anionic and non-ionic surfactants are applied to investigate due to they are widely applied and more discharged into the environmental system.

During operation the membrane filtration, the membrane fouling can continually generate and absorb on the membrane surface. The increase of membrane fouling reduces the movement of solute molecules, thus, it is to be removed. Several researches have been studied the cleaning process by the physical and chemical cleaning. However, the chemical cleaning is much more interesting than the physical cleaning due to it can apply for widely contaminants. There are many types of chemical cleaning that is applied in the membrane filtration such as acid agents (HCl, H_2SO_4, HNO_3), base agents (NaOH, KOH), and complexing agents (EDTA) depending on the contaminants. Generally, the base agents are widely applied for cleaning process in the membrane filtration because it is good removing of organic and inorganic in the wastewater. Thus, in this study, NaOH and 0.1 NaCl were used as a cleaning agents for membrane surface.

CHAPTER III

EFFECT OF SIGLE SURFACTANT AS FEED SOLUTION ON FORWARD OSMOSIS PROCESS

3.1 Introduction

Forward Osmosis process (FO), an innovative technology for the separation process, utilizes the difference in concentration solution to generate an osmotic pressure gradient as the driving force. The diffusion in water molecules continually occurs across a semi permeable membrane from a less concentrated feed solution, to a highly concentrated draw solution (Xu et al., 2010). A semi permeable membrane allows the water molecules and a small amount of salt to permeate through, while most solute/salt molecules are rejected (Cath et al., 2005). The advantages of the FO process have previously been reported, such as, it can be operated at a low or zero hydraulic pressure with a high rejection in a wide range of pollutants in water/wastewater (Cath et al., 2006a). In addition, the FO process is widely applied in many fields (water treatment, wastewater treatment, water reuse, brackish groundwater and seawater desalination) (Cath et al., 2006b, Kravath and Davis 1975, Xu et al., 2006). Like RO, there are many drawbacks which are retarding amid FO performance, for example, solution properties, membrane properties, concentration polarization, and especially, membrane fouling (Cath et al., 2006b, Klaysom et al., 2013b). Typically, municipal wastewater also contains a variety of organic, inorganic substances, and particulates from domestic sources which includes some toxic elements (Lutchmiah et al., 2014). Several studies have stated that the accumulation and interactions between the properties of the membrane and the properties in the foulant are the main causes of flux decline (Lee et al., 2005). Boo et al., (2012) stated that the accumulation of colloidal particles on the osmotic membrane significantly produces flux decline rates due to cake-enhanced osmotic pressure (CEOP) near the membrane surface which reduces the osmotic pressure gradient as a driving force amid the FO process. On the other hand, the organic matters do not affect the FO performance as organic matters attach and fully cover the membrane surface (Lee et al., 2005) due to the deposited organic matters on the active layer of the membrane surface being able to augment more hydrophilic activity at the membrane surface, thereby increasing water diffusion (Valladares Linares et al., 2011, Zhao et al., 2012). Surfactant substances are widely used in many industrial environments; most are applied as detergents for washing. After use, the surfactant molecules would be discharged to the environmental system as domestic wastewater. Therefore, the problem in surfactant fouling on the membrane surface is always observed when the membrane separation is applied for treatment of wastewaters (Kaya et al., 2006). Yang et al (Yang et al., 2005) reported that the relative flux of anionic surfactant decreased gradually in the cross-flow velocity in ultrafiltration, and the adsorption and accumulation of surfactant at the membrane surface can induce more diffusion of water molecules due to the membrane surface becoming less hydrophobic with negative charge in anionic surfactant (Kaya et al., 2011). In the presence of feed solution containing non-ionic surfactant, the interaction with both negatively charged and neutral surfaces can adsorb and act on the membrane properties; however, a basic function of diffusion in water molecules occurs due to interactions of hydrophobic or hydrophilic activity on neutral surfaces (Kaya et al., 2006, Kertész et al., 2008a, Zhao et al., 2015). This means that greater hydrophilic action of the non-ionic surfactant can promote diffusion in water molecules. Nevertheless, the adsorption as well as the accumulation of the surfactant on the membrane surface are the main interaction at the membrane surface amid separation (Markels et al., 1995, Yang et al., 2005). However, the adsorption of surfactants occurs resultant of the inducing of its physical-chemical properties, such as pH of feed solution, cross-flow velocity and the increasing of surfactant concentration in ultrafiltration (Paria and Khilar 2004). Devia et al., (2015) reported that during separation, the transferring of water molecules and salt molecules is critical to the FO process due to concentration polarization (CP), reducing water-flux and inducing membrane fouling (Shibuya et al., 2015). What's more, surfactant adsorption tends to decrease with an increase in feed solution pH due to alkali's ability to decrease the positive charge on the surface, while the increasing of temperature reduces the adsorbed surfactant on the surface due to the fact that improved surfactant solubility results in decreasing adsorption at high temperatures amid the solids phase (Kaya et al., 2011, Kertész et al., 2008a). The increasing of surfactant concentration in feed solution induces more diffusion of water molecules in cross-flow nano-filtration (Kaya et al., 2006). However, some studies have investigated the effect of operating conditions on feed solution containing anionic and nonionic surfactant amid the FO process. Based on the aforementioned reasons, this study focuses on the effect of sodium dodecyl sulfate (SDS) as anionic surfactant, and nonyl phenol ethoxylate (NP-40) as the nonionic surfactant on the osmotic membrane in the FO process. The performance of the FO process under the osmotic membrane for various surfactants was investigated. The main objective was accordingly, to determine the effect of surfactant concentration, cross-flow velocity, and pH of feed solution on the FO process. Moreover, the diffusion of salt molecules was continuously monitored during the FO process.

3.2 Materials and Methods

3.2.1 Solution Chemistry

Sodium dodecyl sulfate (SDS) was selected as the representative anionic surfactant in the environment. Sodium dodecyl sulfate (SDS) was provided (Ajax

Finechem Pty Ltd.) with the molecular weight of sodium dodecyl sulfate (SDS) at 288.38 g/mol ($NaC_{12}H_{25}SO_4$). The critical micelle concentration (CMC) of sodium dodecyl sulfate (SDS) is 8.2 mM (25°C) (1972). For the nonionic surfactant in this research, Tergitol@solution (NP-40) was prepared by Sigma-Aldrich (USA). Critical micelle concentration (CMC) was 232.0 mg/L (25 °C). Feed solution pH was adjusted by 0.02N NaOH and/or 0.02N HCl.

Table 3.1 Summary of the surfactant properties

Surfactant	Type	MW (g/mol)	Abbreviation	CMC (mM)
Sodium dodecyl sulfate	Anionic	288.3	SDS	8.2 mM (25°C)
Nonyl-phenoxy-polyethoxyl ethanol (NP-40)	Non-ionic	602.0	NP-40	232.0 mg/L (25 °C)

3.2.2 Osmotic Membrane

The osmotic membrane (FO-4040) used in this research was provided by Toray Korea (South Korea). Prior to experimentation outset, the membrane was continuously soaked in de-ionized water over 24 h (at 4.0°C). The osmotic membrane was cut according to the size of the membrane cell (length, width, and channel height of 2.60 cm, 7.75 cm, and 0.30 cm, respectively), then, carefully placed between the two chambers of the membrane unit in order to separate the feed and draw solutions. The effective area concerning the osmotic membrane was 20.10 cm^2.

3.2.3 FO operation

The FO experimental setup applied in this study consisted of a bench scale flat-sheet cross-flow FO system. Schematic outcomes of the FO lab-scale cross-flow system can be found in our previous publication (Kaya et al., 2006). The FO system contained a cross-flow membrane cell with internal dimensions of 7.7 cm length, 2.6 cm width and 0.3 cm height, two peristaltic pumps (BT100M/YZ1515x) to circulate draw solution (DS) and feed solution (FS) in corresponding closed loops, solution reservoir tanks and a weighing balance (AND GF-4000, Japan) to continuously record the variation in the DS weight for water-flux computation. An initial volume of feed and draw solution was 2L, and 2L, respectively. Operation time for each experiment was 8 h, with a controlled temperature at 25±0.5°C for all experiments. Figure 3.1 illustrates the FO fouling experiment. Moreover, baseline experiments were conducted to quantify flux decline due to the decrease in the osmotic driving force during the fouling experiments, as the draw solution is continuously diluted by the permeate water. The baseline experiments followed the same protocol as for the fouling experiments except that no foulant was added to the feed solution. The baseline of each experiment was demonstrated for 60 min minus any fouling in the feed solution, then, post data stabilization, the weighing balance began counting automatically. The graphical representation of the fouling experiment is shown in Figure 3.2.

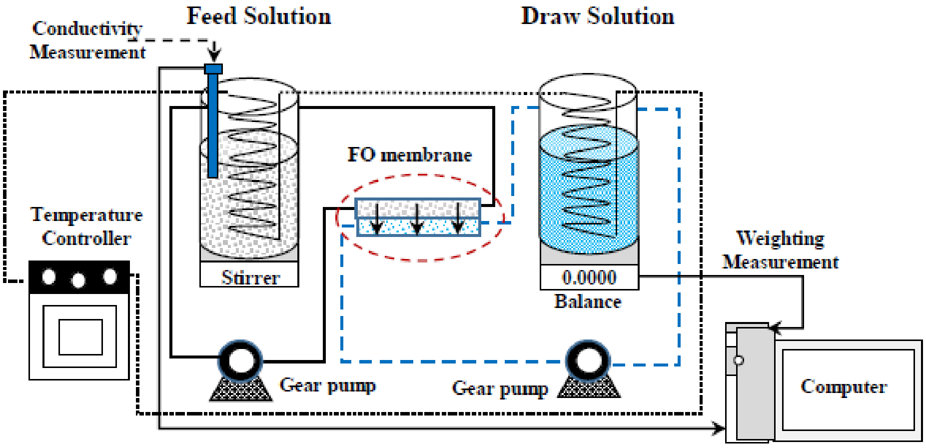


Figure 3.1 Lab-scale of forward osmosis process in fouling experiment

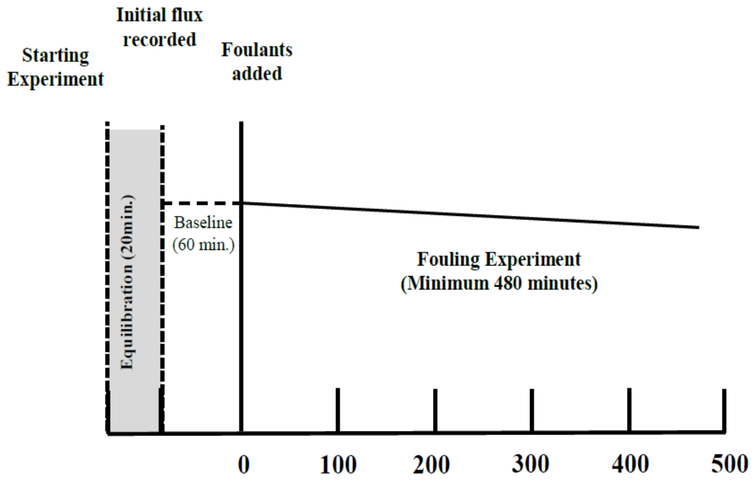


Figure 3.2 Graphical representation of the fouling experiment

3.2.4 FT-IR and Contact Angle measurement

To investigate the surface tension of the osmotic membrane surface post adding an anionic surfactant and non-ionic surfactant, contact angle measurement was applied to demonstrate the hydrophobic activity of the membrane surface. The fouled membrane samples were carefully removed from the membrane unit, air-dried, and kept in storage. The virgin and fouled membranes were measured via contact angle goniometer (Phenix-300, USA). 50 μL of de-ionized water was used to monitor the contact angle of the membrane, and at least 5 contact angle measurements were performed in the study. Furthermore, to understand the fouling phenomena, the adsorption of anionic and non-ionic surfactant on the osmotic membrane were characterized by FT-IR. Spectrum One System (Perkin-Elmer, USA) in the range of 450 $cm^{-1}$to 4000 cm^{-1} was applied.

3.3 Results and Discussion

3.3.1 Impact of the operating condition in pristine membrane

To understand the phenomenon, the diffusion of the water molecules and the solute in the FO process across the structure of the membrane needs to be further discussed. Several researches have stated that the structural membrane contributes to the transport of water molecules and prevents reverse salt diffusion (Phillip et al, 2010; Ang, W.S. and Elimelech, 2008). In the FO mode, the active membrane layer typically faces a feed side and the support layer faces a draw side. The water molecules continuously diffuse across the active layer, and then transport inside the supporting layer of the membrane. As represented in Figure 3.3, below the thin and active layer of high water permeability, finger-like macrovoids were formed. The small pores at the surface decrease the wet-ability of the membrane and the macrovoids decrease the mass transfer resistance, resulting in an increasing of the mass transfer of water molecules (Lalia et al., 2013). For clear investigation, the structures of both the RO membrane and osmotic membrane were observed on the active layer and cross-section using scanning electron microscope (SEM). In the osmotic membrane, the structure formed like macrovoids (Figure 3.3b), which promoted mass transfer resistance. Furthermore, the macrovoids structure of osmotic membrane reduced the increase in internal concentration polarization (ICP) in the supporting layer. In contrast, the RO membrane structure was illustrated asymmetrically and tortuously (Figure 3.3d).

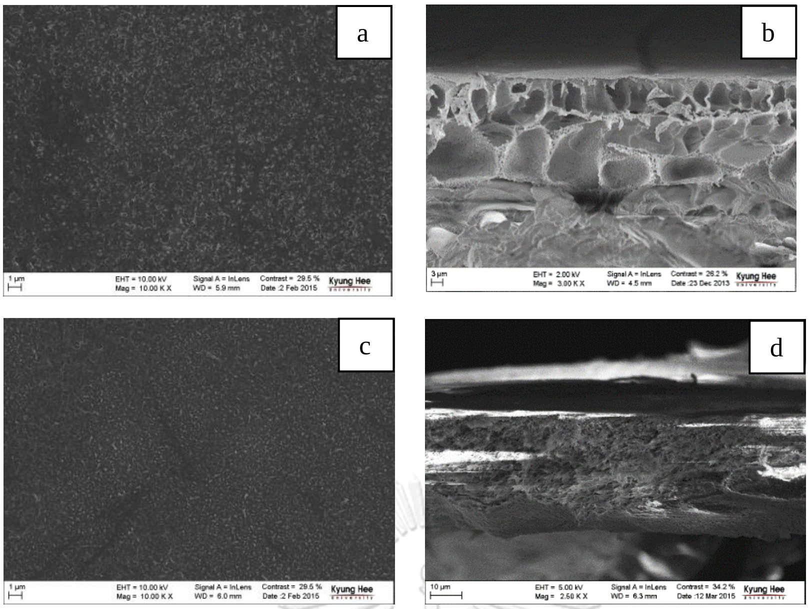


Figure 3.3 Cross section of Osmotic membrane (a= active layer, b=cross-section) and RO membrane (c=active layer, d=cross section)

To investigate the effect of the draw solution concentration on the FO performance, the experiments were conducted in conditions under different concentrations of 0.5, 1.0, 2.0 and 3.0 M NaCl, respectively. The cross-flow velocity of both the feed and draw solutions was fixed at 7.03 cm/s, and the absence of surfactant in feed solution was 10 mM NaCl. The experimental conditions are demonstrated in Table 3.2, and the osmotic pressure equation is calculated using

$$\pi = iMRT$$

where; π = osmotic pressure, i = van't Hoff's factor, M = molar concentration of solution (mol/L), R= ideal gas constant(0.08206 $L.atm.mol^{-1}.K^{-1}$) and T= temperature in Kelvin (K)

Table 3.2 Data for FO run under different draw concentration (without foulant)

Active Layer		Supporting Layer	
NaCl (M)	π (atm)	NaCl(M)	π (atm)
0.01	0.48	0.5	24.5
0.01	0.48	1.0	48.9
0.01	0.48	2.0	97.8
0.01	0.48	3.0	146.7

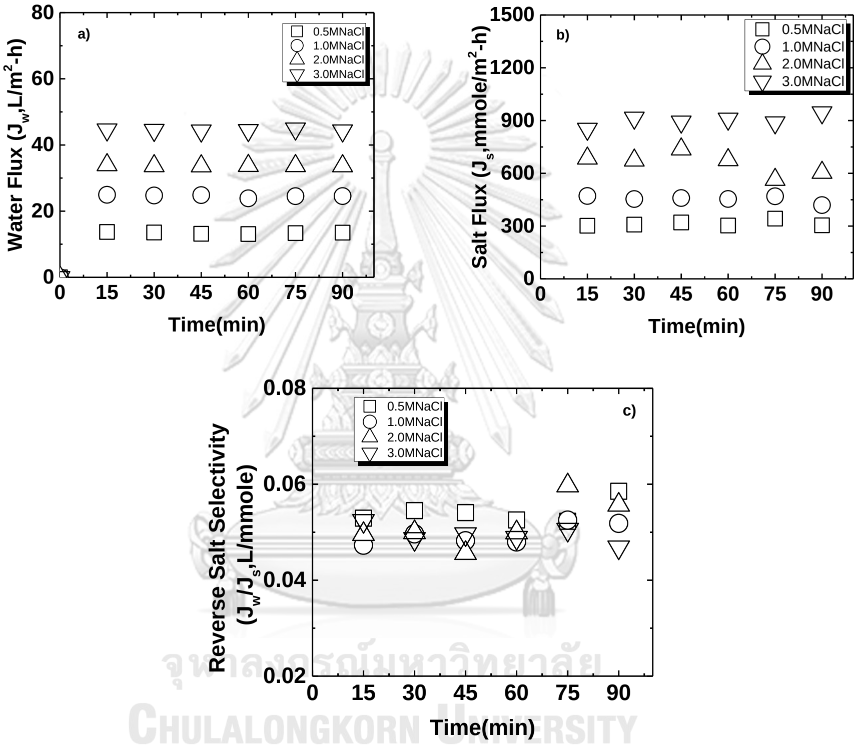


Figure 3.4 Effect of draw concentration on the FO using the pristine membrane

Results of these experiments illustrate that the diffusion of water molecules increased when the draw solution was a cumulative solution concentration. This was due to the evaluated draw solution-concentration leading to an increase in the osmotic pressure gradient as a driving force amid the FO process (Figure 3.4a). In addition, it is also well-know that when the osmotic pressure gradient of the FO process is elevated, not only more movement of water molecules occurs, but also the diffusion of salt molecules increases (Hoek and

Elimelech 2003) as shown in Figure 3.4b. Furthermore, the ratio of the volume of water produced per mole of draw solute lost is reported as a function of reversal salt selectivity (Phillip et al., 2010). Interestingly, although the water flux is increased but the reversal salt selectivity is stable (Figure 3.3c) due to properties of osmotic membrane. In addition, to more clearly investigated, the averages of water flux and the relationship of increased diffusion in water molecules on the salt flux and reversal salt selectivity were showed in Figure 3.5.

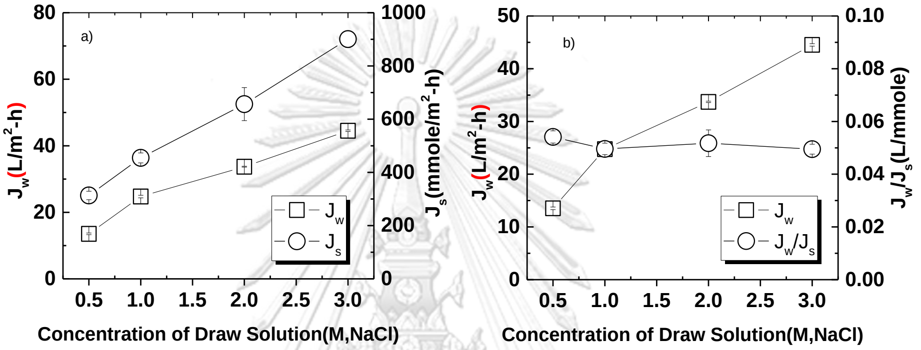


Figure 3.5 Relation of water flux-salt flux (a), and water flux-reversal salt selectivity (b)

In the case of the cross-flow velocity to be further examined, the effects of the cross-flow velocity on the FO process, cross flow velocities of both the feed and draw solution were equally adjusted (0.48, 0.92, 7.03, and 10.5 cm/s). The concentration of feed solution was fixed at 10 mM NaCl, and draw solution concentration was 1.0 M NaCl for all conditions. Table 3.6 demonstrates osmotic pressure. The water flux of the FO process was highest at 10.5 cm/s of velocity followed by 7.03 cm/s, 0.92 cm/s and 0.48 cm/s, respectively. It can be clearly observed that the increasing of cross-flow velocity mitigates flux decline amid the FO process, yet reversal salt selectivity did not exhibit any significant change amid FO process. Lee et al., (1981) stated that the retarding in flux decline was observed when the FO process increased in cross-flow velocity. Moreover, we are able to effectively control FO fouling by optimizing hydrodynamic operating conditions. The averages of water flux and the relationship of increased diffusion in water molecules on the salt flux and reversal salt selectivity were showed in Figure 3.7.

Table 3.3 Data for FO run under different cross-flow velocity (without foulant)

Cross-flow velocity (cm/s)	Active Layer		Supporting Layer	
	NaCl(M)	π (atm)	NaCl (M)	π (atm)
0.48	0.01	0.48	1.0	48.9
0.92	0.01	0.48	1.0	48.9
7.03	0.01	0.48	1.0	48.9
10.5	0.01	0.48	1.0	48.9

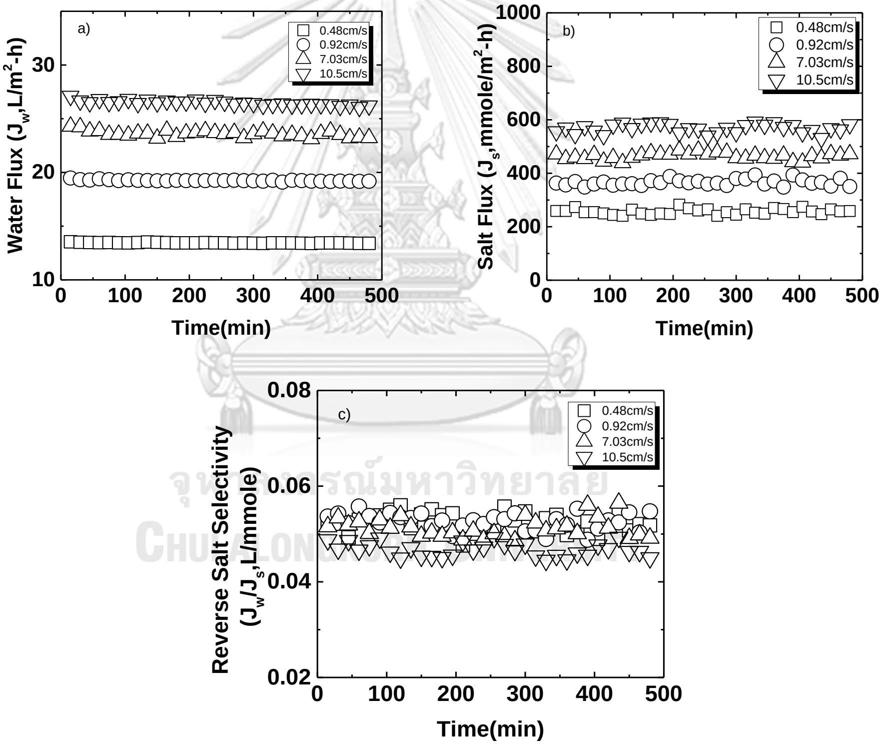


Figure 3.6 Effect of cross-flow velocity on the FO using the pristine membrane

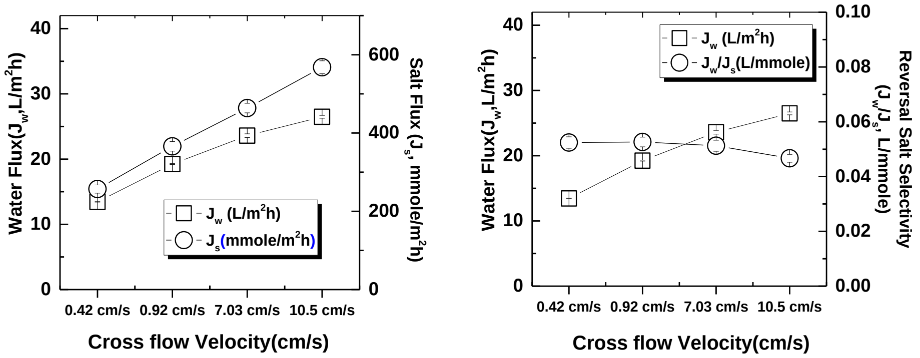


Figure 3.7 Relation of water flux-salt flux of pristine membrane (a) and water flux-reversal salt selectivity (b)

To investigate the influence of pH in the feed solution minus any surfactants in the feed solution, pH in the feed solution was carefully adjusted by utilizing 0.02M HCl and 0.02 M NaOH. The cross-flow velocity of both feed and draw solution was fixed at 7.03 cm/s, and 1.0 M NaCl of draw solution. The osmotic pressure under differences of pH in feed solution is shown in Table 3.4. It was clearly seen that the water flux in the FO process increased when the pH of the feed solution was elevated (Figure 3.8). To further explain the behavior of the flux during FO operating, the relation to the interaction between the membrane surface properties and the negative charge in the bulk solution was applied. Li et al., (2011) stated that the carboxyl groups mainly play a role on the membrane surface at higher pH due to carboxyl groups coating the membrane surfaces; the membrane surfaces would subsequently become more hydrophilic, then increase in water diffusion. However, reversal salt selectivity did not show any significant change in the FO process due to the when more water flux was increased the salt molecules were also diffused from the draw solution.

Table 3.4 Data for FO run under different pH feed solution (without foulant)

pH in feed solution	Active Layer		Supporting Layer	
	NaCl (M)	π (atm)	NaCl (M)	π(atm)
4.0	0.01	0.48	1.0	48.9
6.0	0.01	0.48	1.0	48.9
7.0	0.01	0.48	1.0	48.9
9.0	0.01	0.48	1.0	48.9
10.0	0.01	0.48	1.0	48.9

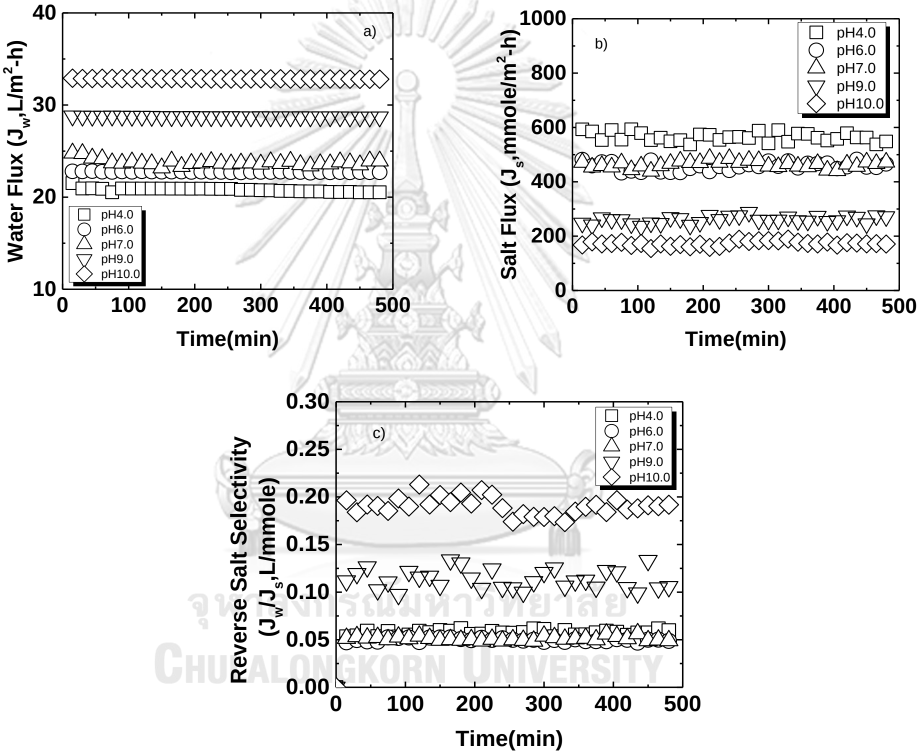


Figure 3.8 Effect of pH in feed solution on the FO using the pristine membrane

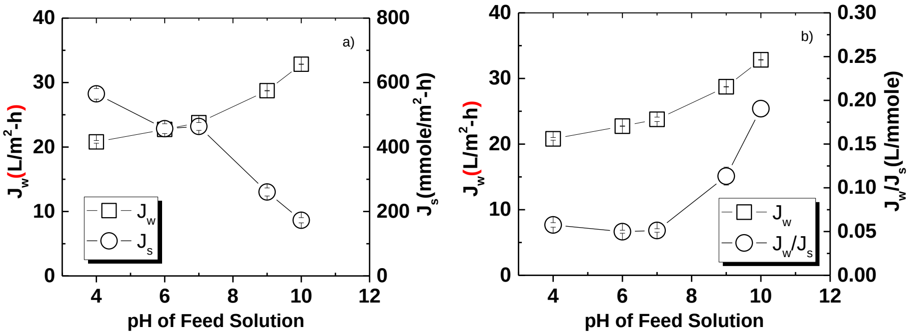


Figure 3.9 Relation of water flux-salt flux pristine membrane (a) and water flux-reversal salt selectivity (b)

3.3.2 Effect of operation condition on forward osmosis with surfactant

3.3.2.1 Effect of cross flow velocity on FO performance

In order to investigate the influence of cross-flow velocity on FO performance the concentration of SDS in feed solution was 2.37 g/l, and 0.232 g/l of NP-40 in the FO process. The experiments were conducted at different cross-flow velocities of 0.48, 0.92, 7.03, and 10.5 cm/s, respectively. As plotted in Figure 3.10, it is clearly observed that the water flux was slightly increased when the cross flow velocity of the FO process was carefully adjusted from 0.48 to 10.5 cm/s. It was highest in the case of feed solution containing SDS, followed by NP-40, and the pristine membrane. Accordingly, there are two ways to describe this phenomenon; 1) the increasing of cross-flow velocity is the main mechanism; nevertheless, due to a lower cross flow velocity, the adsorption of surfactant molecules occurs easier near the osmotic membrane surface. Then, the dilutive ECP plays a role as a barrier for the diffusion of water molecules. On the contrary, higher cross-flow velocity decreased the boundary layer thickness, thus the absorption of the surfactant decreased in the membrane surface, thereby increasing in the water diffusion (Nguyen et al., 2013, Zhao et al., 2012). 2) the adsorbed SDS surfactant on the membrane surface induced hydrophilic activity. During FO operating, even though the increase in cross-flow velocity was elevated, there may be a small amount of SDS surfactant adsorbed in the membrane properties, hence the increasing in negative charge. In the presence of feed solution containing non-ionic surfactant, the mechanism process is quite similar to the anionic surfactant. However, the molecules of nonionic surfactants onto both negative and neutral surfaces can be adsorbed on the membrane surface depending upon hydrophobic and hydrophilic action, as head groups of nonionic surfactants can be bound to neutral surfaces. In this study, the hydrophilic process plays a major role in the increasing of water flux. For additional investigation, the contact angle was applied to measure the absorbed membrane. In our experiment, the pristine membrane post application in the FO process was 46.57. Nonetheless, the NP-fouled membrane could not measure the contact angle due to the dropping liquid (water solution) quickly passing the fouled membrane. Consequently, the NP-fouled membrane was more hydrophilic. To further examine, the change in membrane properties was investigated. Typically, the FO was negatively charged at 7.0, the carboxylic functional groups were found when the FTIR spectroscopy was applied. In other words, more hydrophilic was clearly observed from carboxylic functional groups on the active layer of the membrane. In this study, the significant appearances of pristine and surfactant-fouled membrane were found at 1700 cm^{-1} and 1100 cm^{-}1, respectively. Hence, FTIR spectra were only illustrated within the range of 1000-2000 cm^{-1}. Fig 3.10 clearly proved that the vibration band of the surfactant-fouled membrane at 1700-1750 cm^{-1} was possibly indicative for C=O stretching of carboxylic acid, and C-O stretching of carboxylic acid or C–N stretching at 1000-1100 cm^{-1}, respectively.

Furthermore, the diffusion of salt molecules across the osmotic membrane was also continually investigated during FO operating. Suh and Lee (Suh and Lee 2013) discovered more rapid dilution of reverse diffusing draw solute when cross-flow velocity was elevated: this is the decreasing of the ECP effect. In the case of a pristine membrane, the increase of cross-flow velocity significantly promotes the diffusion of salt molecules crossing the membrane surface (Figure 3.9b). These results are similar to a previous publication (Suh and Lee 2013). On the other hand, the behavior of salt flux significantly increased even when the cross-flow velocity of the FO process was adjusted from 0.48 to 10.5 cm/s and the feed solution was added along with the surfactant. This phenomenon might be explained by the interaction of surfactant molecules and properties on the osmotic membrane surface, including the interaction of salt molecules under different kinds of surfactants (Yang et al., 2005). More adsorption of the surfactant on the membrane causes the layer-surfactant to act as a resistance in the diffusion of water molecules at the lower cross-flow velocity. Additionally, hydrophobic interaction between the hydrophobic tail of the surfactant and the membrane-constricted membrane pores reduced the reverse salt diffusion of Na^+ (Nguyen et al., 2015). In contrast, it was clearly observed that the accumulation of surfactant would be removed with the increasing cross-flow velocity, then, the salt flux is slightly increased as seen in Figure 3.9b. However, little increase in salt flux was found due to a small amount of surfactant absorbed on the membrane surface, thus reducing salt diffusion in the draw solution.

Table 3.5 Data for FO run under cross-flow velocities with single surfactant

Velocity (cm/s)	Active Layer				Supporting Layer	
	NaCl (M)	π (atm)	SDS (g/l)	NP-40 (g/l)	NaCl (M)	π (atm)
0.48	0.01	0.48	2.37	0.232	1.0	48.9
0.92	0.01	0.48	2.37	0.232	1.0	48.9
7.03	0.01	0.48	2.37	0.232	1.0	48.9
10.5	0.01	0.48	2.37	0.232	1.0	48.9

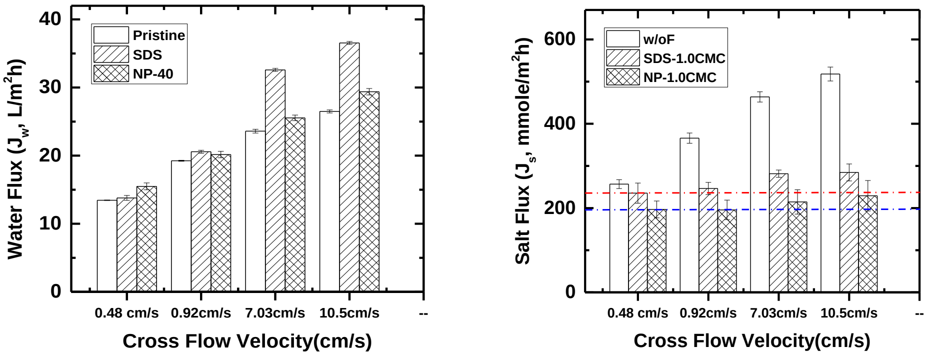


Figure 3.10 Effect of cross flow velocity on the FO performance with single surfactant

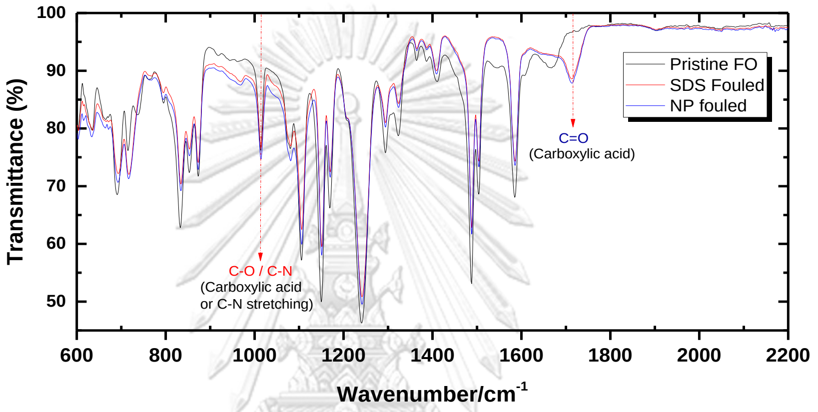


Figure 3.11 FTIR spectra of the pristine and surfactant-fouled by SDS and NP-40

3.3.2.2 Effect of pH in feed solution on FO performance

To investigate the effect of pH in the feed solution on FO performance, total ionic strength in the feed solution was fixed at 10 mM NaCl. Two types of surfactant were utilized in this experiment. The initial volumes of draw solution and feed solution were both 2.0 L, and cross flow velocity was fixed at 7.03 cm/s. The pH in feed solution was varied from 4.0 to 10.0. Figure 3.12 illustrates the effect of different pH levels in the feed solution on the FO performance. Results indicate that the water flux amid the FO process increased after the pH in feed solution was elevated from 4.0 to 10.0 in the presence of surfactant, especially, anionic surfactant (SDS). These results could be additionally explained by the change in characteristics of the membrane as well as the adsorbed functional groups of the surfactant. Normally, the polyamide on the active layer of the reverse osmosis membrane surface is a positively charged at a low pH, and negatively charged at high pH (Childress and Elimelech 1996). Furthermore, absorbed surfactants on the membrane surface promote the negative charge on the membrane surface, resulting in more diffusion of water molecules amid the FO process.

Meanwhile, the water flux was significantly increased when feed solution pH was adjusted from 4.0 to 10.0. Conversely, the diffusion of salt molecules did not follow the amount of water molecules. As seen in Figure 3.12b, salt rejection was highest when the FO experiment was operated with the pristine membrane. Further increases in salt rejection were revealed in the anionic surfactant, followed by non-ionic surfactant and pristine membrane respectively. These results can be explained in relation to the change in membrane surface properties due to the adsorbed surfactant. At high pH, the feed solution is more negatively charged from the hydroxyl group (OH^-) and a polyamide; they were then obstructed by the filtration process. More accumulation of negative charge on the active layer of the membrane surface induced more diffusion of water molecules, at the same time, it behaved as a barrier to increase salt rejection resistance. Childress and Deshmukh (Childress and Elimelech 1996) also mentioned that the covering of anionic surfactant on the surface of the reverse osmosis membrane augmented resistance as well as salt rejection. Besides that, the adsorption of surfactant significantly decreased salt rejection at low solution pH due to being positively charged (Childress and Elimelech 1996, Kaya et al., 2006, Zhao et al., 2015).

Table 3.6 Data for FO run under pH in feed solution with single surfactant

pH in feed solution	Active Layer				Supporting Layer	
	NaCl (M)	π (atm)	SDS (g/l)	NP-40 (g/l)	NaCl (M)	π (atm)
4.0	0.01	0.48	2.37	0.232	1.0	48.9
6.0	0.01	0.48	2.37	0.232	1.0	48.9
7.0	0.01	0.48	2.37	0.232	1.0	48.9
9.0	0.01	0.48	2.37	0.232	1.0	48.9
10.0	0.01	0.48	2.37	0.232	1.0	48.9

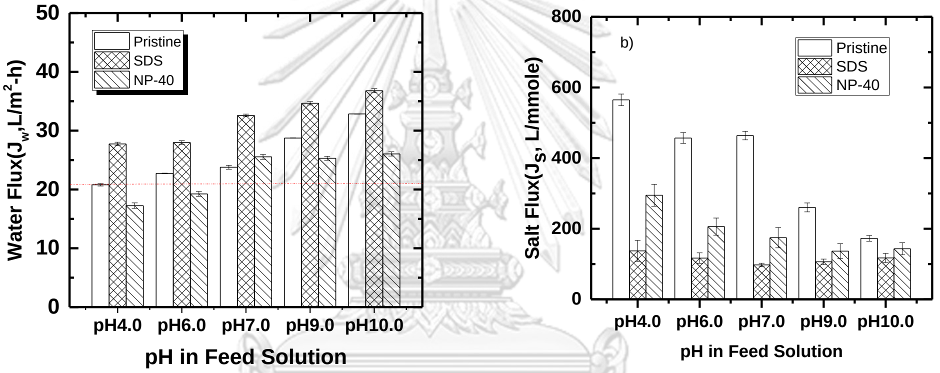


Figure 3.12 Effect of pH in feed solution on the FO performance.

3.3.2.3 Effect of concentration in surfactant on FO performance

To investigate the effect of increased concentration of anionic as well as non-ionic surfactant on the FO performance, cross-flow velocity was fixed at 7.03 cm/s and 7.0 of pH in the feed solution. The concentration of both surfactants was varied. Figure 3.13 presents the water flux-time curves in FO mode. The addition of SDS to the feed water resulted in the water flux increasing. In case of feed solution containing SDS, the behavior of flux can be further explained by the adsorption of SDS on the active layer of the membrane. As seen in Figure 3.13a, water flux amid the FO process slightly increased after adding the SDS into the feed solution. The molecules of SDS would be transferred and tended to be adsorbed on the membrane surface. The accumulated SDS surfactant on the membrane rendered greater negative charge on the active layer of the osmotic membrane. This indicates that the membrane surface is more hydrophilic, consequently inducing greater diffusion in water molecules. Zhao et al., (2012) also stated that the hydrophilic groups in surfactant would interact at the solid-solution interface, resulting in the increasing of diffusion in water molecules. In terms of non-ionic surfactant fouling experiments, the mechanisms of process are quite similar to the anionic surfactant. Kaya et al., (2006) stated that the molecules of nonionic surfactants onto both negative and neutral surfaces can be adsorbed on the membrane surface. The interaction of process will occur depending on head groups, though the hydrophilic as head groups of nonionic surfactants are dominant in this fouling experiment (Kaya et al., 2011). According to our results, it was revealed that hydrophilic binding becomes dominant, resulting in decreasing contact angle. Figure 3.13b illustrates salt flux post-adding of surfactant into the feed solution. As a result, the salt flux was decreased when the feed solution was filled with the surfactant. Still, the diffusion of salt molecules did not demonstrate any difference despite the surfactant concentration being adjusted from 0 to 2.37 g/l. This indicates that the adsorption of surfactant on the membrane surface has the ability to significantly reduce the movement of salt molecules.

Table 3.7 Data for FO run under various surfactant concentration

SDS (g/l)	NP-40 (g/l)	Active Layer		Supporting Layer	
		NaCl (M)	π (atm)	NaCl (M)	π (atm)
0.237	0.0232	0.01	0.48	1.0	48.9
1.185	0.116	0.01	0.48	1.0	48.9
2.370	0.232	0.01	0.48	1.0	48.9

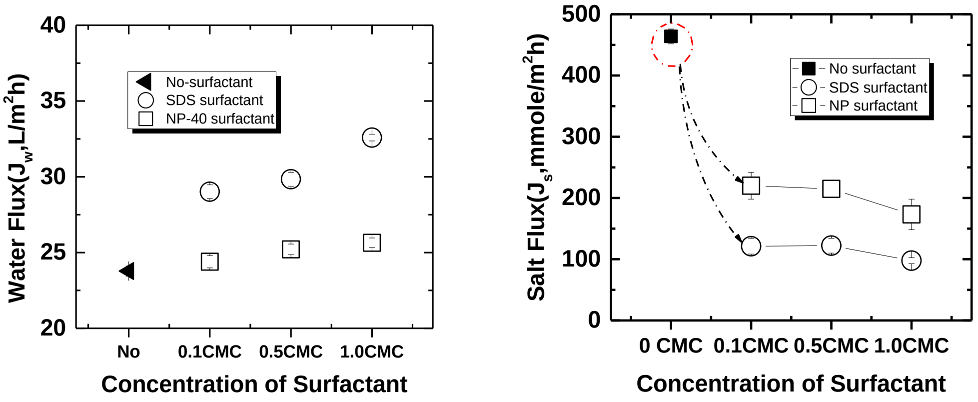


Figure 3.13 water flux and salt flux of FO process under various concentration

3.3.4 Reversal Salt Selectivity (J_w/J_s)

During the FO process, reverse salt diffusion in the draw solution is one of the most significant parameters due to its effects as an osmotic driving force on the forward diffusion of water molecules, in other words, it influences the FO performance. To explain further, the ratio of the volume of water produced per mole of draw solute lost is reported as a function of reversal salt selectivity (Phillip et al., 2010). In this study, there are three operating conditions to investigate the reversal salt selectivity on the FO process as illustrated in Figure 3.14. In the case of cross-flow velocity, reversal salt selectivity did not exhibit any significance when the pristine membrane was employed as the barrier in the FO process. Conversely, reversal salt selectivity significantly increased with the adding of surfactant into the feed solution, in particular, feed solution containing SDS. The concentrative ECP was applied to elucidate the mechanism in this study. The accumulation of surfactant on the membrane surface continuously occurred during FO operation. Furthermore, the increase in cross-flow velocity shear reduced the generated surfactant molecules, then, it induced greater diffusion of water molecules. Nevertheless, even though the water molecules were increased when the cross-flow velocity was adjusted, the rate of salt diffusion was quite stable. Therefore, the reversal salt selectivity would increase with the increased cross-velocity flow in both the feed and draw solutions. In the case of pH in the feed solution, as described in the previous section, the diffusion of water molecules would increase due to the negative charge which is generated by hydroxyl groups as well as the surfactant. In addition, the salt flux did not alter insignificance during FO operating. At low pH, less negative charge in the bulk occurred, as a consequence, the rate of diffusion in solute did not show any significance. Notwithstanding, the reversal salt selectivity increased when the feed solution pH was adjusted due to the membrane surface inducing more diffusion in water molecules than the salt molecules. In case of surfactant concentration, the reversal salt selectivity of anionic surfactant (SDS) was rather stable even when surfactant concentration was varied from 0 to 2.37 g/l. While nonionic surfactant is slightly increased at low concentration, it is quite stable at concentrations of 0 to 2.37 g/l.

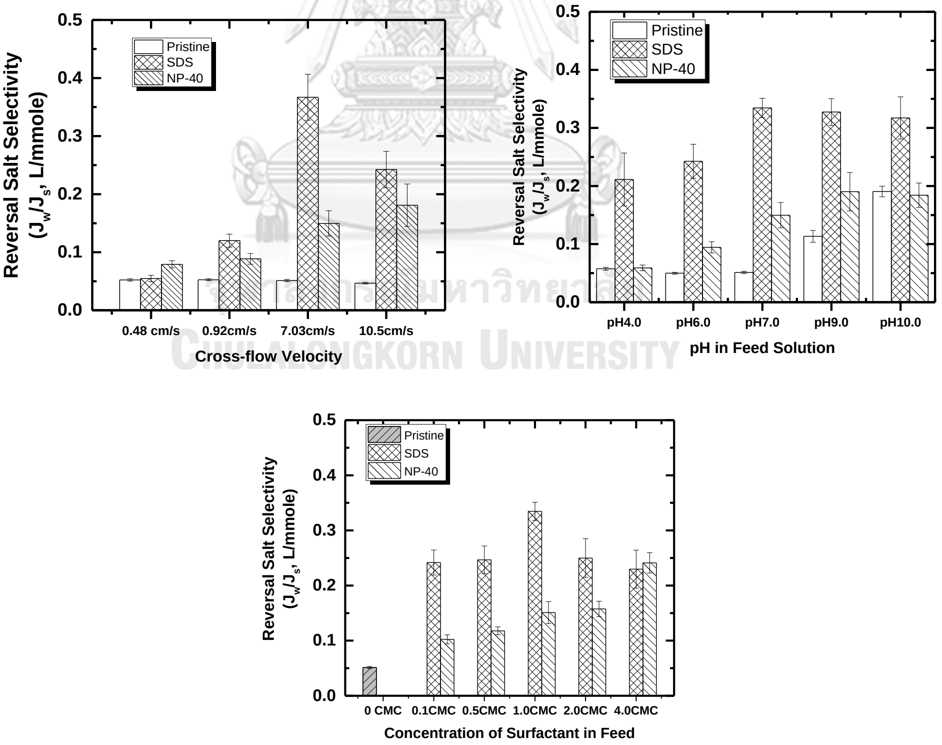


Figure 3.14 Reversal Salt Selectivity of FO process on the FO

3.4 Conclusions

In this research, the effects of different operating conditions (cross flow velocity, pH of feed solution, surfactant concentration) were investigated amid the FO process. The results revealed that the diffusion of water molecules increased with cross-flow velocity, feed solution pH, and surfactant increasing. High diffusion in water molecules amid the FO process seemed to be mainly dependent on the accumulation of negative charge on the active layer. Furthermore, deposits of negative charge on the membrane surface induced the diffusion of water molecules, whereby increasing FO performance. Contrariwise, the diffusion in salt molecules decreased after adding the surfactant into the feed solution due to the surfactant layer performing as a resistance, resulting in the reduction of salt flux. For the reversal salt selectivity under different operating conditions of the FO process, the results indicated that the reversal salt selectivity increased with cross-flow velocity and feed solution pH augmenting.

CHAPTER IV

EFFECT OF COMBINED SURFACTANT AS FEED SOLUTION ON FORWARD OSMOSIS PROCESS

4.1 Introduction

At present, surfactants are widely used in industry such as in metal processing, textiles, food processing, pharmaceuticals and paper industries (Kaya et al., 2006). They are also used in the production of many household cleaning agents(Kaya et al., 2009). Unfortunately, most surfactants are commonly released into the environmental system after use; as a result causing severe environmental issues. Although a small amount of surfactants are discharged into water sources, they are minimally removed or eradicated by the environment due to surfactants reacting with various substances in water (Azarteimour et al., 2016, Zhao et al., 2015). There are several methods which have been broadly applied to separate surfactants from the environment, for instance, chemical precipitation, adsorption and biological degradation (Kaya et al., 2009). Membrane processes are attractive technologies in that they can be effectively applied for both removal and recovery. However, the performance of the process is dependent on not only properties of the membrane, but also surfactant structure. Kaya et al., (2009) stated that microfiltration (MF) and ultrafiltration (UF) can be achieved in terms of removing surfactants from wastewater and other water. Nevertheless, surfactant monomers can pass through membranes. This is unlike nano-filtration (NF) which can be effectively applied to remove the surfactant at low concentrations in permeate (Kertész et al., 2008b). Moreover, reverse osmosis (RO) is commonly employed to produce water purification due to its high rejection salt molecules, low contaminants and monovalent ions from wastewater (Xie et al., 2017). Baudequin et al., (2014a) stated that the flux decline amid the RO process was dependent upon adsorption and the membrane-surfactant interaction (hydrophobic). Kishimoto,Kimura (2012) stated that the polyamide thin-film composite RO membrane has the ability to separate the surfactant from water, and also, the rejection rate of three types of surfactants (CTAB, SLS, Triton X-100) is over 99%. Furthermore, high permeability of the RO process depended on low concentration of surfactant and more on a negatively charged surfactant (Ang et al., 2011, Kishimoto and Kimura 2012, Mai et al., 2016). As well as that, the covering of the anionic surfactant on the RO membrane promotes hydrophilic grouping, resulting in increased water diffusion (Ang et al., 2011). Although the RO process displays high separation in surfactant from wastewater, the drawbacks are that it is easier to generate membrane fouling, and a subsequent decrease in performance. Recently, forward osmosis (FO) technology, a physical phenomenon, refers to the diffusion of water molecules across a selectively permeable membrane by applying differences in osmotic pressure gradient (Cath et al., 2006a). In contrast to the RO process, forward osmosis does not apply hydraulic pressures amid operation. In actual fact, it exhibits high rejection efficiency in contaminant separation and retarding amid membrane fouling generation (Cath et al., 2006a, Holloway et al., 2007). Several researches have applied FO technology to both treat and recover water or substances, i.e. water purification, wastewater reclamation, industrial wastewater treatment, desalination, food processing, and pharmaceuticals (Holloway et al., 2007, Petrotos et al., 1998, Zhang et al., 2012). Accordingly, it would appear that FO technology can effectively treat contaminants with high removal efficiency and as such is widely applied in many fields. Nonetheless, there are still certain drawbacks, for example, membrane properties (concentration polarization), scaling, and especially, FS characteristic (Boo et al., 2012, Lay et al., 2012b). Zhao and colleagues(Zhao et al., 2015) revealed that the high separation in sodium dodecyl benzene sulfonate (SDBS) increased with flow velocity in both sides whereby increasing and decreasing temperature and concentration. Nevertheless, although the impact of single surfactant in rejection has been investigated, at present, the behaviors of flux decline and FO performance in anionic, non-ionic, and mixture surfactant have not exactly been widely demonstrated. During operation of the FO process, single or mixture surfactant molecules will continuously interact with the membrane properties (active layer). The accumulation/adsorption of surfactant molecules either governors the mitigation or aggravation of concentration polarization; or fouling on the osmotic membrane. In this work, we focused on the behavior of in-flux decline of sodium dodecyl sulfate (SDS) as an anionic surfactant, and of tergitol@solution (NP-40) as a nonionic surfactant by employing the FO process. The normalized flux value for single and mixture surfactant as a function of time was observed throughout FO experimentation. In addition, fouled-osmotic membrane was analyzed by means of change in membrane surface properties. Contact angle measurement was applied as a sign of the membrane's wet ability.

4.2 Materials and Methods

4.2.1 Chemicals

In this work, two types of surfactant were employed as a representative in effluent. Sodium dodecyl sulfate (SDS) was used as an anionic surfactant (Ajax Finechem Pty Ltd., MWSDS is 288.38 g/mol), Tergitol@solution (NP-40, Sigma-Aldrich, USA) was applied as nonionic surfactant, and combined solution (both anionic and nonionic surfactant in equal concentration) was also utilised. In addition, humic acid (HA) was selected as a model organic foulant (Sigma-Aldrich (USA) in the effluent. For a more complete mix, stock HA-solution was carefully prepared by dissolving the HA (received in powder form) in deionized (DI) water and mixed over 24 h prior to use. In case of particulates in the effluent, colloidal particles (CML) were selected. In order to control solution pH during experiment operation, 0.02N NaOH and 0.02N HCl were applied.

4.2.2 Osmotic Membrane

In this work, a commercial high water diffusion membrane was provided by Toray Korea (South Korea). Prior to experimentation, the membrane was continuously soaked in de-ionized water over 24 h (at 4.0^{o}C). Surfactant-fouling experiments were conducted using a laboratory scale cross-flow high osmotic membrane. For all conditions of surfactant fouling experimentation, feed solution (surfactant solution) makes contact with the active layer of the osmotic membrane, and the draw solution (NaCl solution) comes into contact with the supporting layer. The diffusion and transportation of water molecules then occurs on the effective area of the osmotic membrane (20.10 cm^{2}). To prepare the membrane sample, membrane sizing was carefully cut according to membrane unit specification (length, width, and channel height of 2.60 cm, 7.75 cm, and 0.30 cm, respectively). A new membrane sample was always prepared and applied for each surfactant-fouling experiment.

4.2.3 FO surfactant fouling operation

Two peristaltic pumps (BT100M/YZ1515x) were utilised to circulate the solution (feed and draw solution) of corresponding closed loops. In order to measure the change in reservoir tanks, a weighing balance (AND GF-4000, Japan) automatically counted and continuously recorded the variation of draw solution. For each fouling experiment, an initial volume of feed and draw solution was carefully fixed at 2L, operational time was continuously run within 8 h, with control temperature at 25±0.5°C. Prior to the outset of all surfactant fouling experiments, a baseline experiment was conducted to observe the trend in flux decline. In addition, the baseline of each experiment would be demonstrated for at least 60 min without any surfactant molecules containment in the feed solution. After stabilizing influx, SDS (anionic surfactant) or NP-40 (nonionic surfactant) was carefully added into the feed solution, then, a weighing balance was employed to count automatically.

4.3 Results and Discussion

4.3.1 Impact of cross-flow velocity on combined surfactant using FO

In this work, FO process was conducted on the mixture solution as a side feed. These conditions are similar to the single surfactant fouling experiment, which is the impact of cross-flow velocity, pH in feed solution, and mixture concentration. In case of impact of cross-flow velocity, mixture concentration was prepared equally between SDS (2.37 g/l) and NP-40 (0.232 g/l). The flow-rate of both feed and draw solution was varied (0.48 m/s, 0.92 m/s, 7.03 m/s, and 10.5 m/s respectively). Likely single surfactant demonstrates that water flux increased with the increase in cross-flow velocity. In addition, as seen in Figure 4.1, at the cross-flow rate of 10.5 cm/s, the normalized flux (J/J_o) was less disturbed, following 7.03, 0.92, and 0.48 cm/s respectively. The result is quite similar to the single surfactant amid a fouling experiment. Therefore, the mechanism of the fouling experiment was elucidated in the cross-flow velocity of single surfactant which is due to the higher cross-flow velocity reducing the accumulation of mixture surfactant, and then increasing in diffusion of water molecules as already explained. Besides that, the diffusion of salt is one of the important phenomena in need of investigation due to it directly relating to the decrease of the net driving force. Figure 4.1a clearly illustrates the mixture surfactant salt flux. As a result, the salt flux is quite stable as compared with the virgin osmotic membrane. Meanwhile, the reversal salt selectivity of mixture surfactant is increased due to the elevation of cross-flow velocity being able to reduce the accumulation, and as a result, increasing the diffusion of water molecules (Figure 4.1b).

Table 4.1 Data for FO run under different cross-flow velocity for combination

Velocity (cm/s)	Active Layer			Supporting Layer		Flux in 8 h (LHM, average)
	NaCl (M)	π (atm)	Mix	NaCl (M)	π (atm)	
0.48	0.01	0.48	1.0	1.0	48.25	25.825
0.92	0.01	0.48	1.0	1.0	48.25	27.717
7.03	0.01	0.48	1.0	1.0	48.25	38.198
10.5	0.01	0.48	1.0	1.0	48.25	43.741

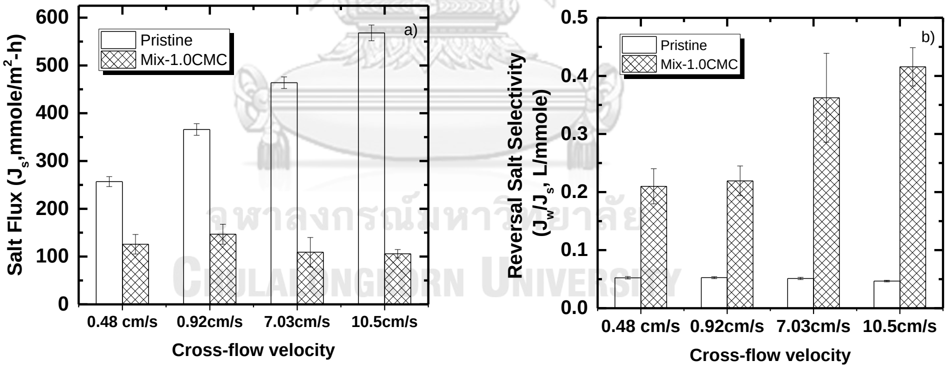


Figure 4.1 Effect of combination surfactant on the FO process under different cross-flow velocity

4.3.2 Impact of pH in feed solution on mixture surfactant using FO

To investigate the effect of pH in feed solution on the FO process, the pH in feed solution was carefully prepared employing 0.02N NaOH. The ionic strength was fixed at 10 mM NaCl. Table 4.2 displays the fouling experiment conditions. Results indicated that the water flux increased when the pH in feed solution was elevated from 4.0 to 10.0. In contrast, the salt flux was reduced (Figure 4.2a) at high pH in the feed solution. This can further elucidate the mechanism of the FO process. In case of impact of pH in feed solution, a higher pH in feed solution not only exhibits less impact on performance, but also the mixture surfactant. Consequently, it was indicated that a negatively charged polyamide (active layer) and hydrophilic bonding on the osmotic membrane surface hold a main role in the increased diffusion of water molecules amid the FO process. Our mixture fouling experiments are notably similar to Kaya and colleagues, whereby the adsorption mechanisms of mixture solutions on the membrane surface prevailed similar to the adsorption of a single surfactant. In addition, the reversal salt selectivity under various pH in feed solution was also investigated. Outcomes visibly revealed that the reversal salt selectivity increased when the pH in feed solution was elevated (Figure 4.2b). Outcomes can be further elucidated using the relationship between the diffusion of water molecules and salt molecules. At elevated pH in feed solution, water molecules presented greater passing on the osmotic membrane due to hydrophilic on the surface. At the same time, the diffusion of salt molecules is retarded, resulting in increasing reversal salt selectivity (Figure 4.2b).

Table 4.2 Data for FO run under different pH feed solution for combination

pH feed solution	Active Layer			Supporting Layer		Flux in 8 h (LHM, average)
	NaCl (M)	π (atm)	Mix (CMC)	NaCl (M)	π (atm)	
4.0	0.01	0.48	1.0	1.0	48.25	26.149
6.0	0.01	0.48	1.0	1.0	48.25	27.984
7.0	0.01	0.48	1.0	1.0	48.25	38.198
9.0	0.01	0.48	1.0	1.0	48.25	38.435
10.0	0.01	0.48	1.0	1.0	48.25	40.599

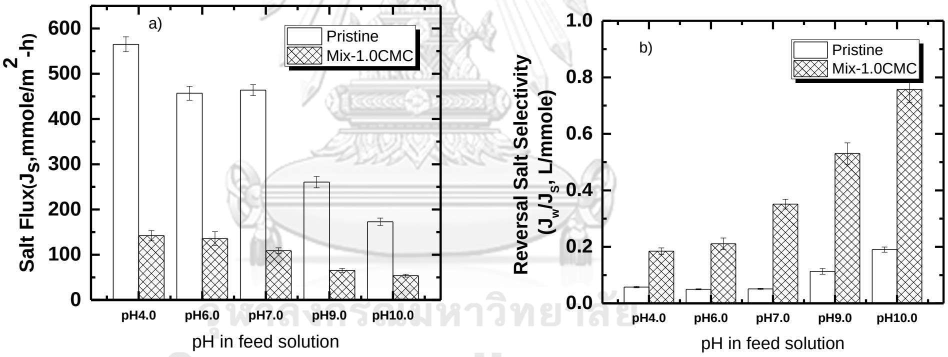


Figure 4.2 Effect of combination surfactant on the FO process under different pH in feed solution

4.3.3 Impact of mixture concentration on the FO process

For further investigation, observed membrane fouling behavior due to the increase in concentration was investigated. Table 4.3 illustrates the water flux of mixture surfactant under different concentrations. Results indicated that the water flux is decreased after adding 0.5 CMC of mixture surfactant into the feed solution, however, the water flux increased when the concentration of mixture was elevated from 1.0 to 2.0 CMC as seen in Table 4.3. The phenomena in water flux can be further elucidated using the properties of the osmotic membrane surface and mixture surfactant. In the FO process, the molecules of mixture surfactant tended to continually absorb into the osmotic membrane surface due to the hydrophobic interactions near the surface, resulting in the water slightly declining. The water flux would slightly increase after adding the mixture surfactant. Zhao et al., (2015) mentioned that surfactants were formed in monomeric form in both non-polar and polar solvents at low concentrations. In contrast, micelles formed at the solid-solution interface, in which the hydrophilic groups orientated towards the water. This kind of micelles absorbed into the membrane surface and made the membrane more hydrophilic, resulting in greater water flux.

Furthermore, the diffusion of salt molecules under mixture surfactant was also investigated. The decreasing in salt flux amid the FO process was significantly observed when the concentration of mixture surfactant was elevated, yet the salt flux of 0.5 CMC in mixture concentration increased due to more adsorbed mixture molecules (Figure 4.3a), thereby creating additional diffusion of salt molecules. Notably, the diffusion of water molecules per salt molecules was also reported as a function of reversal salt flux. As indicated in Figure 4.3b, the reversal salt flux under mixture surfactant suggested that the reversal salt flux of feed containing mixture surfactant was increased due to the interactions between mixture surfactant molecules and the properties of the active layer (more negatively charged). Deposited mixture surfactant molecules on the membrane surface significantly induced more hydrophilic in addition to the transport of ions in the forward and reverse directions which were retarded by the negative charge (Phillip et al., 2010; Xie et al., 2013). In addition, Hancock et al. (2009) also mentioned that more hydrophilic on the membrane surface is attributed to the increasing membrane salt (NaCl) permeability coefficient.

Table 4.3 Data for FO run under different mixture concentration

Mix (CMC)	Active Layer			Supporting Layer		Flux in 8 h (LHM, average)
	NaCl(M)	π (atm)	Velocity (cm/s)	NaCl (M)	π (atm)	
0	0.01	0.48	7.03	1.0	48.25	38.198
0.5	0.01	0.48	7.03	1.0	48.25	32.146
1.0	0.01	0.48	7.03	1.0	48.25	38.197
2.0	0.01	0.48	7.03	1.0	48.25	41.614

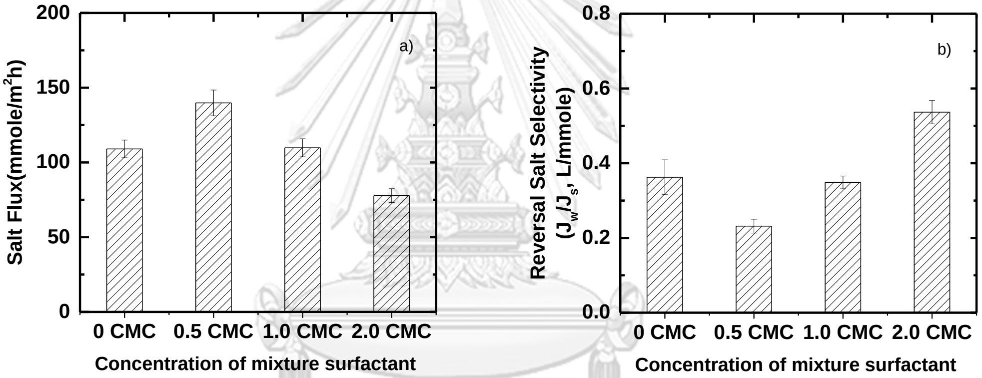


Figure 4.3 Effect of combination surfactant on the FO under different concentration

4.3.4 Comparison in flux decline under different kinds in surfactant

To provide greater overall understanding of surfactant fouling experimentation, the behavior of flux decline is investigated and compared in this section. Specific conditions were selected for comparison amid the different kinds of surfactant. The concentration in each solution was selected at 1.0 CMC, flow rate was fixed at 7.03 m/s, and the pH feed solution was set at 7.0. Table 4.4 clearly presents water flux under different types of surfactant in the FO process. The findings indicate that the water flux was highest with the mixture surfactant, followed by SDS and NP-40, respectively. The mechanism of interaction on the process via the adsorption of surfactant on the membrane surface, was applied to provide supplementary explanation in this section. Due to mixed-solution consisting of anionic and non-ionic surfactants, it would indicate that the surfactant molecule was implicitly increased. During operation, the surfactant molecules were transferred then attached to the osmotic membrane via sieving mechanism. The accumulation of mixed-surfactant continuously occurred and generated on the membrane surface, and subsequently retarded the diffusion of water molecules. Meanwhile, the adsorption of single surfactant less affected the osmotic membrane, especially, anionic surfactant (SDS).

To be further investigated, one of the important determinants in the FO process is the continuous diffusion of salt molecules from the draw solution to the feed solution during operation. In the case of salt flux, the diffusion of salt molecules passed more across the pristine membrane (Figure 4.4a) due to the covering of surfactant on the active layer of the osmotic membrane surface, resulting in the retarding of the diffusion of salt molecules as already explained. What's more, the diffusion of water molecules per salt molecules was reported as a function of reversal salt selectivity. Figure 4.4b shows the reversal salt selectivity under different types of surfactant. Reversal salt selectivity increased when the FO process was operated with mixture surfactant as feed solution, followed by SDS and NP-40, respectively. The experimentation results contributed to the interactions between the surfactant properties and the properties of the osmotic membrane surface i.e. the adsorption of surfactant on the active layer promoted the hydrophilic, resulting in the increase in water molecules and the retarding of salt molecules.

Table 4.4 Data for FO under various types surfactant

Condition	Active Layer			Supporting Layer		Flux in 8 h (LHM, average)
	NaCl (M)	π (atm)	Conc.	NaCl (M)	π (atm)	
Pristine	0.01	0.48	0	1.0	48.25	23.778
SDS	0.01	0.48	0.5	1.0	48.25	32.585
NP-40	0.01	0.48	0.5	1.0	48.25	25.645
Mix	0.01	0.48	0.5	1.0	48.25	38.197

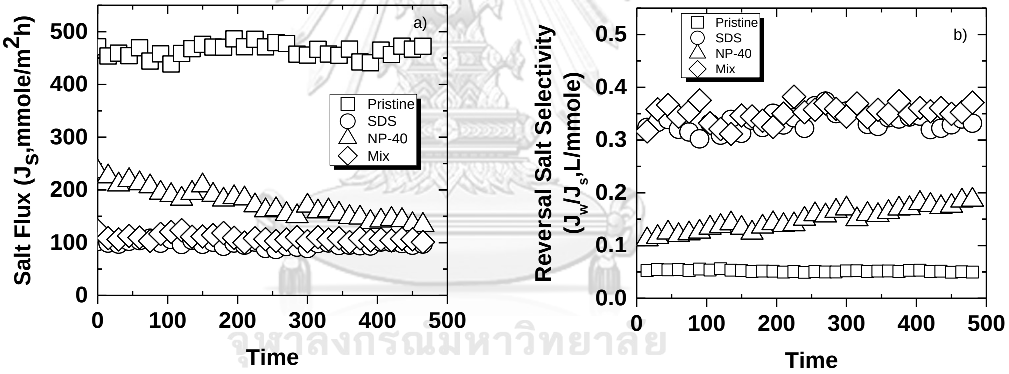


Figure 4.4 Summary the surfactant fouling experiment on FO process

To be further examine, the change in membrane properties was investigated. Typically, the FO was negatively charged at 7.0, the carboxylic functional groups were found when the FTIR spectroscopy was applied. In the other word, more hydrophilic was clearly observed carboxylic functional groups on the active layer of membrane. Figure 4.5 clearly indicates that the properties of osmotic membrane did not changes in a functional groups on the active layer.

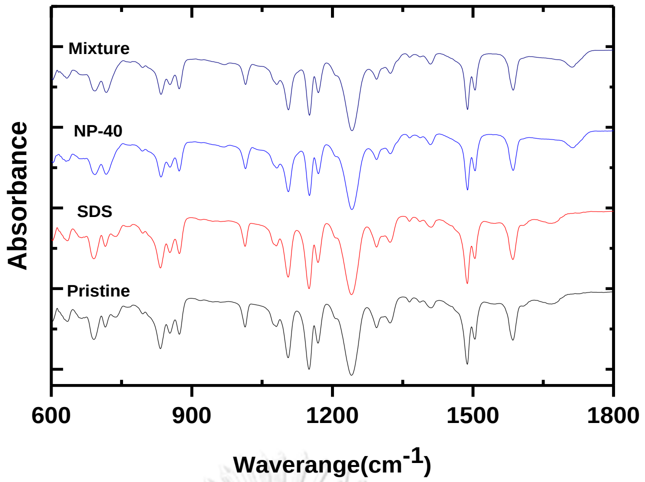


Figure 4.5 FTIR spectra of the pristine and surfactant-fouled by SDS, NP-40, and mixture surfactant

4.3 Conclusions

In this study, the FO process of mixture surfactant (SDS+NP-40) was investigated under operational conditions (mixture surfactant concentration, cross-flow velocity, and pH in feed solution). Results revealed less of an effect on FO performance when incorporating cross-flow velocity increasing, elevated pH in feed solution and surfactant concentration increasing. Interactions between the osmotic membrane properties (active layer) and properties of surfactant were attributed to the behavior of flux amid the FO process. These interactions are similar to the single surfactant reaction as reported and explicated in the previous section; that is to say, the increasing in cross flow velocities retarded adsorption, and then increased the diffusion in water molecules. In addition, reduced hydrophobic of mixture surfactant occurred due to the pH in feed solution being elevated, which thusly induced the diffusion of water molecules. In all probability the mechanism of single surfactant and the hydrophilic as a head group of mixture surfactant takes a major role in affecting less of an impact amid the FO process.

CHAPTER V

CLEANING OF COMBINED SURFACTANT UNDER DIFFERENT TYPES OF CHEMICAL CLEANING AGENT

5.1 Introduction

Forward Osmosis (FO) refers to the process of the diffusion of water molecules across the selectively permeable membrane from a diluted feed solution to a more concentrated draw solution by utilizing the osmotic pressure gradient as a driving force (Cath et al., 2006b, Klaysom et al., 2013a). Nowadays, several publications have indicated that the FO process is widely applied in various fields such as in industrial wastewaters (Holloway et al., 2007), wastewater reclamation (Cath et al., 2005), desalinating seawater (Kravath and Davis 1975), and drinking water processing (Kessler and Moody 1976). One of the main challenges concerning FO is the influence of foulants in the feed solution and/or draw solution as well as the flux recovery process. According to the concept of FO, there are two types of solution which need to be prepared; namely, the feed solution and the draw solution. The feed solution should be produced at lower concentration. However, raw wastewater effluent is generally applied as the first priority of the feed solution amid FO in a real situation. Additionally, it is well-know that wastewater typically consists of various foulants such as dissolved organic matter, microorganisms, suspended solids, and inorganic scales including surfactants as mixed-solution (Zhou et al., 2011). Consequently, the effect of those foulants in FO can be remarkably noticeable amid observation. Fouling is generally generated by the attachment of the foulants on the membrane surface. The cake formation of foulants can affect the performance of membrane processes including the reduction in permeate quality and the change in membrane surface characteristics (Cath et al., 2006b, Kessler and Moody 1976). In fouling experimentation, colloidal particles are usually selected as representation of suspended solids and biocollids in the effluent (Srisurichan et al., 2005, Tang et al., 2011). The influence of colloidal particles has been reported in the reverse osmosis (RO) process. Colloidal particles cause more significant permeate flux decline in reverse osmosis (RO) due to the higher accumulative mass of particles on the membrane surface, an increase of the ionic strength, as well as particle size (Klaysom et al., 2013a). Tang et al., (2011) stated that the deposition of such colloidal particles on an RO or NF membrane forms a cake layer which can adversely affect the membrane flux due to the cake layer hydraulic resistance and/or cake-enhanced osmotic pressure (CEOP). Additionally, humic acid (HA) has been identified as one of the major foulants amid the membrane process, and it is generally applied to investigate the influence of organic matters in processing (Srisurichan et al., 2005). Tang et al., (2011) reported that flux declines were negligible for the ranges of humic acid concentration, ionic strength, and pH studied (Tang et al., 2007). Furthermore, the increase in humic acid deposition on the membrane surface led to a substantial decrease in membrane salt (NaCl) permeability coefficient, but did not result in a significant decrease in the membrane pure water permeability coefficient (Zhou et al., 2011). The individual influence of foulant (HA molecules or colloidal particles) has also been investigated in the FO process. Several studies reported that the FO process significantly decreased when the colloidal particles were used as foulants (Boo et al., 2012, Hoek and Elimelech 2003). On the contrary, HA molecules did not play any significant role in the FO process (Subramani et al., 2009). Nevertheless, the impact of combined foulants in the feed solution and/or the draw solution have previously undergone little investigation.

Typically, raw wastewater not only contains humic acid and particulates but also a plethora of other substances. Surfactant molecules are the predominant foulant commonly found in domestic wastewater (Zhou et al., 2011). Several researches have reported that the surfactant can reduce the performance of membrane separation (Boehm and Quinn 1976, Guo et al., 2012). Moreover, the adsorption of surfactant can significantly reduce the flux of the RO process due to membrane-surfactant hydrophobic interaction (Baudequin et al., 2011). Furthermore, surfactant molecules were separated on the polyamide thin-film composite RO membrane, with efficiency of rejection at greater than 99% due to negatively charged surfactant (Ang et al., 2011, Kishimoto and Kimura 2012, Mai 2013). Subsequent to the covering of foulants on the active layer, recovery is a key process amid membrane separation. There are two popular types of cleaning process; cleaning agents and physical process. Several researchers have stated that the osmotic membrane displays less attachment on the surface and can be easily cleaned with hydraulic increase (Mi and Elimelech 2010, Valladares Linares et al., 2014). Additionally, CTA-FO membranes were effectively performed upon with different types of cleaning agents such as 0.8% sodium ethylene-di-amine tetra-acetic acid (EDTA), and 1% Alconox as a commercial cleaning reagent (Wang et al., 2010b).

However, researches and information on chemical cleaning of the osmotic membrane are very limited, thus remaining a challenge in terms of the FO process. In this study, we examined and compared the behavior in flux decline of combined surfactant incorporating different foulants (humic acid, colloids, and boron), and chemical cleaning methods (DI-water, 0.1 M NaCl, NaOH (pH11)). Water flux and salt flux were also investigated.

5.2 Materials and Methods

5.2.1 FO membrane

Osmotic membrane used in this research was provided by CSM Woongjin Chemical Inc. (South Korea). The effective membrane area of each experiment was 20.15 cm2. The membrane unit was built with a length, width, and channel height of 2.60 cm, 7.75 cm, and 0.30 cm respectively. Membrane size was cut according to the membrane cell (2.6 cm x 7.75 cm). An FO membrane sample was inserted between the two chambers of the membrane unit aimed at separating the feed and draw solutions.

5.2.2 Test solutions

In terms of single foulant, three types of solutions were utilised as a feed solution in this research depending on the condition of each experiment (humic acid, colloidal particles, boron). Draw solutions were prepared by dissolving sodium chloride (NaCl) in Milli-Q water (2.0 M NaCl in 2L). The feed solution was applied and fixed with corresponding draw solution concentration. Humic acid (Sigma-Aldrich, St. Louis, MO) used in this study was selected as a model organic foulant. HA stock solution (1.0 g/l) was prepared by dissolving HA powder in Milli-Q water, and the solution was stirred for at least 24 hrs. Prior to use yellow-green fluorescent carboxylated modified latex (CML) particles (1μm diameter; Magsphere, Pasadena, CA, USA) were selected as colloidal particles in this research. 10 mg/l boron was also applied.

5.2.3 Lab-scale of FO fouling experiment

The initial volume of the draw solution was 2.0 l and feed solution 4.0 l, with each fouling experiment operated in a closed-loop. The cross-flow velocity of both draw and feed solution was adjusted to 7.03 cm/s by employing a gear-pump (Longer Pump WT3000-1FA). The temperature of both draw and feed solution was controlled at 21±0.5 °C via a thermostat controller. The draw solution was placed on a digital balance and permeate flux amid the FO process was continuously recorded in real-time via a weighing machine (AND GF-400 digital weighing). Simultaneously, the diffusion of salt molecules across the membrane from the draw solution to the feed solution was monitored as a conductivity value (Vernier, USA). Duration for each experiment was 8 hrs, including the stable flux. Prior to each experiment, the FO process needs to have a stable flux before adding foulant into the solution. In this study, the baseline of each experiment was performed for 60 min. Once the water flux became more stable, the fouling experiment was initiated by adding exact calculated amounts of foulant solution to the feed reservoir. Each baseline experiment was continuously performed without the foulant, and the resulting flux curves were employed as a baseline to compare foulant impact. Prior to investigating the performance of chemical cleaning agents in the FO process, virgin osmotic membrane was continually fouled with various types of foulant (SDS, NP-40, humic acid, colloidal particles, and boron). The initial baseline performance was performed throughout 60 min. The combined foulant was carefully added into the feed solution, then the fouling experiment was continuously carried out over 5 h. At the conclusion of FO fouling experimentation, the feed solution was disposed of and chemical cleaning solution was added to the feed solution in order to clean the fouled membrane.

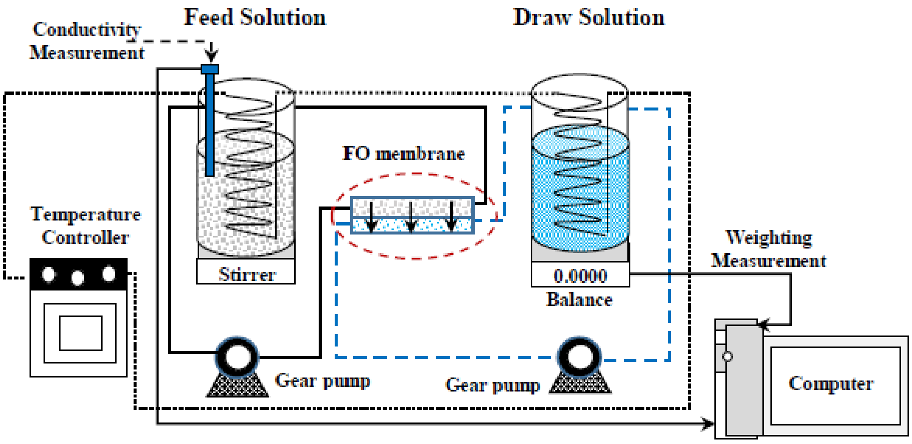


Figure 5.1 Schematic diagram of forward osmosis (FO) process

5.2.4 Foulant in FO fouling experiment

Organic fouling experiment

Humic acid (HA) was chosen as the model organic matter (Sigma-Aldrich (USA). It was used as a model organic foulant at 100 mg/L. For the stock solution (1000.0 mg/l), HA solution was produced by dissolving HA molecules into deionized-water. Prior to the outset of each experiment, HA solution has to be stirred for more than 24 hrs. in order to be completely mixed into a homogeneous solution. The following are the characteristics of the Sigma Aldrich humic acid (Table 5.1).

Table 5.1 Sigma Aldrich humic acid properties

Description	Properties
MW_w	1557
$SUVA_{254}$	0.089

Colloidal fouling experiment

CML particles (Yellow-green fluorescent carboxylated modified latex, Pasadena, CA) were applied as model colloids in wastewater. In addition, the deposition of colloidal particles was observed. The concentration of colloidal particles can be calculated as per below:

Table 5.2 Magsphere CML particles properties

Description	**Characteristic**
Particle diameter	1 μm
Percent solids	2.5%
Charge density	0.022 meq/g
Surface group	carboxylic

Number of CML particles/L of feed solution

$$N = \frac{Total\,Volume}{Particle\,Volume} = \frac{V_{CM\,L}(\%solids)}{4/3\pi r^3}$$

Example

the volume of feed solution is 1000 ml

$$= \frac{10^7}{ml} x1000\ ml(feed) = \frac{V_{CM\,L}(0.025)}{4/3\pi(0.5x10^{-6}m)^3}\,x\,\frac{1m^3}{10^6 ml} = 2.094x10^{-4}\,ml$$

*Therefore, V_{CML} in 1 L of feed = 0.2094 ml

5.2 Results and Discussion

5.3.1 Influence of feed solution containing HA and CML

Prior to investigating the effect of foulant on the FO process, measuring the characteristics of fouling in solution is an important factor in the membrane process due to its ability to alter membrane surface properties (Hong and Elimelech 1997). Thus, it is necessary to investigate the basic properties of fouling before interaction with the osmotic membrane surface. Hong,Elimelech (1997) mentioned that the charge of HA molecules can affect the membrane surface, and it is also influential amid process performance. What's more, HA molecules can appear more or less negatively charged with different ionic strength (Srisurichan et al., 2005). So, in this research, properties of HA molecules in the feed solution were demonstrated. To investigate solution charge ionic strength was prepared with two types of feed solution i.e. di-ionized water and 10 mM NaCl. Results illustrated that the molecular weight (MW_w) of HA molecules was 1555.0 and $SUVA_{254}$ 0.089, respectively. In addition, zeta potential value of HA solution with a de-ionized (non-ionic strength) and 10 mM NaCl were -44.77 mV and -37.02 mV, respectively. As a result, the negative charged in the feed solution in both non-ionic strength and elevated ionic strength was clearly observed. Accordingly, negative charge plays a predominant role in the course of the FO process during interaction between HA molecules and the active layer of the osmotic membrane surface.

To compare the effect of individual foulants the influence of feed containing foulants on FO performance was also demonstrated. The concentration of draw solution was prepared and fixed at 1.0M NaCl for all fouling experiments. In this section, two types of foulants were selected as representatives of organic matter (humic acid) and particulates (colloids). Table 5.3 illustrates the averages of water flux post FO system processing which was continually run over 8 h. Results clearly indicated that the water flux was highest when the FO process was employed as feed solution, followed by colloidal particles, and pristine membrane, respectively.

Additionally, the normalized flux and salt flux were investigated. Figure 5.2 clearly shows the normalized flux of FO fouling experimentation under different types of feed solution. Results indicated that the normalized flux amid the FO process was significantly decreased when the FO system employed feed solution containing colloidal particles. Moreover, the normalized flux was quite stable with feed solution containing HA molecules (as seen in Figure 5.2a). One of the important factors in the FO process is the diffusion of salt molecules due to their continual retarding of the osmotic gradient pressure amid the FO process, which was also observed in this experiment. Figure 5.2b clearly illustrates the salt flux under different types of foulant in the FO process. The salt flux was highest when the FO process was operated in feed solution containing colloids, succeeded by pristine osmotic membrane and fouled HA molecules, respectively. The mechanism of phenomena is subsequently elucidated.

Table 5.3 Data for FO run under different foulants

Condition	Active Layer		Supporting Layer		Flux in 8 h (LHM, average)
	NaCl (M)	π (atm)	NaCl (M)	π (atm)	
10mM	0.01	0.48	1.0	48.25	24.705
50 mg/l HA	0.01	0.48	1.0	48.25	26.808
10^7/ml CML	0.01	0.48	1.0	48.25	22.229

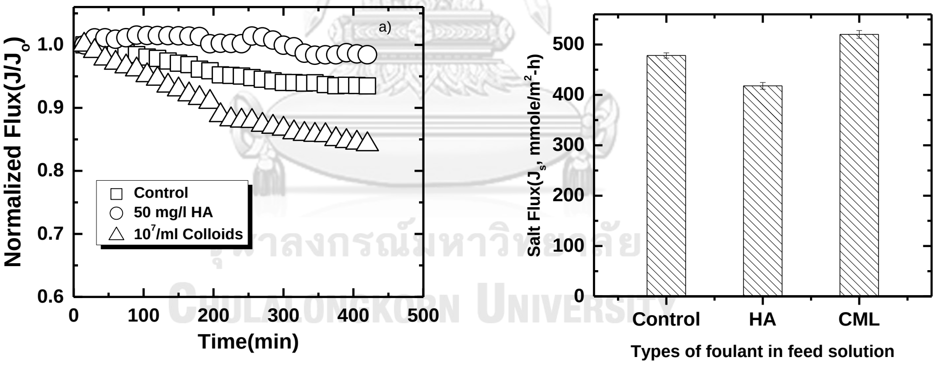


Figure 5.2 Normalized flux (a) and Salt flux (b) of FO fouling experiment

To further investigate, the observed membrane fouling behavior and SEM image were applied in each condition of this research. As shown in Figure 5.2, three flux decline curves of each experiment are presented under different draw solution types, where HA molecules and colloidal particles were employed as organic foulant and suspended solid foulant, respectively. The results clearly illustrate that the flux decline was much more significant when the FO was continuously operated with the feed solution containing colloidal particles in all draw solution types. On the other hand, the feed solution containing HA molecules did not play any significant role amid FO performance. In addition, the deposition of both colloidal particles and HA molecules was clearly observed. The FO fouling mechanism can be explicated via cake-enhanced osmotic pressure (CEOP) (Boo et al., 2012). The depreciation of water flux was primarily attributed to the attached colloidal particles on the membrane surface in the presence of feed solution mixed with the colloidal particles. The deposited colloidal particles close to the membrane surface confined the back diffusion of salt molecules, thereby resulting in increased concentration in the feed solution. Furthermore, the accumulated salt concentration near the membrane surface increased the osmotic pressure reducing the osmotic gradient pressure of the FO process. In other words, it reduced FO performance. Consequently, the formation of the colloid layer strongly promoted the elevated osmotic pressure at feed side.

Unlike colloidal particles, the FO fouling mechanism of the feed solution containing HA molecules does not contribute to the cake-enhanced osmotic pressure (CEOP). Even though a greater number of HA molecules in the feed solution markedly mantled the membrane surface, the behavior of flux decline was not explicitly induced by the deposited HA molecules. Xie et al., (2014) reported that the formation of a HA acid fouling layer caused the membrane surface to be more negatively charged, then, the membrane surface becomes less hydrophobic. The hydrophilic of the membrane surface increased the diffusion of water molecules; this means that FO performance was also augmented. Hence, in this experiment it can be concluded that the FO performance was considerably decreased in the presence of feed solution containing colloidal particles. The deposited colloid layer near the membrane surface greatly promoted the elevated osmotic pressure, thereby resulting in severely reduced FO performance. On the contrary, HA molecules did not play any significant role in flux decline due to the greater negative charge increase in the hydrophilic membrane surface nor retarding in the flux decline amid the FO process.

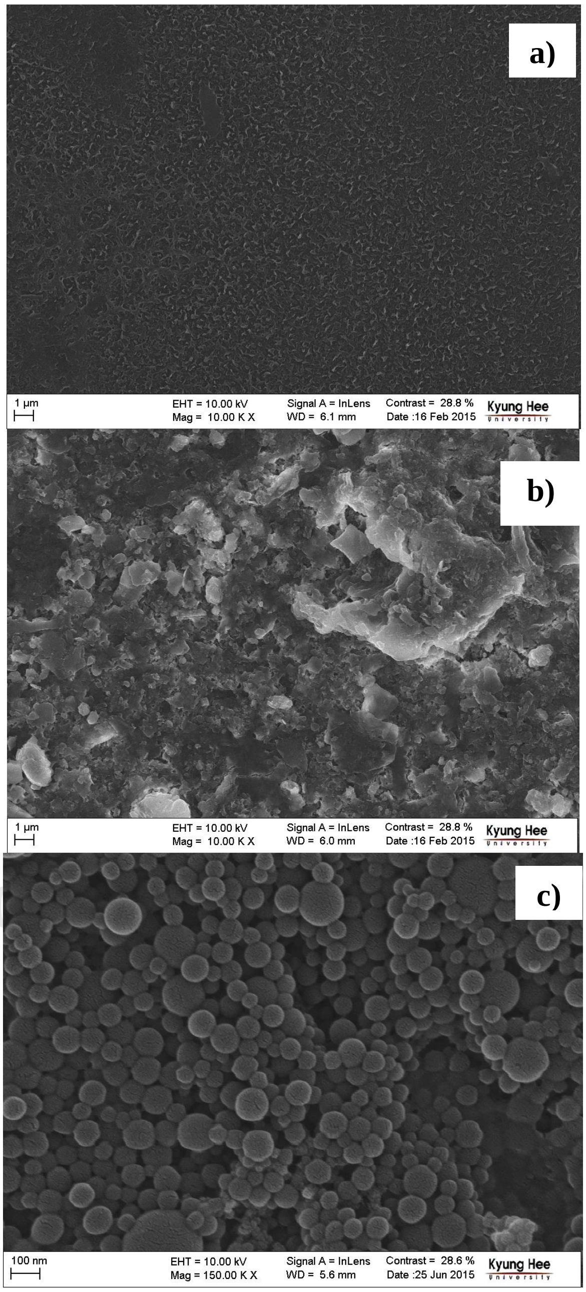


Figure 5.3 FE-SEM images of the membrane surface (active layer), virgin membrane (a), HA fouled membrane (b), and Colloids fouled membrane (c).

5.3.2 Reversal salt selectivity

During operating, one of the important determinants in ODMPs is continuous diffusion of salt molecules from the draw side to feed side. Salt molecules can successively diffuse across the FO membrane (Phillip et al., 2010, She et al., 2012). The changing of salt concentration between the feed solution and the draw solution contributed to the osmotic pressure gradient of the FO process, in other words, the altered osmotic pressure of both the feed and draw solution directly influenced FO performance. The ratio of the volume of water produced per mole of draw solute lost is reported as a function of reversal salt selectivity (Phillip et al., 2010). In this experiment, reversal salt selectivity was employed to report the changing of sodium chloride and the diffusion of water molecules.

Figure 5.4 clearly presents reversal salt selectivity under various draw solution concentrations. Findings visibly show that reversal salt selectivity is highest in the presence of feed solution containing HA molecules, and lowest in the presence of feed solution containing colloidal particles. For further observation, the behavior of the reversal salt selectivity and conductivity was continuously monitored under different types of foulants including the various draw solution types. Srisurichan et al., (2005) stated it slightly increased when the feed solution contained HA molecules; on the other hand, the feed containing colloidal particles was quite stable amid reversal salt selectivity. What’s more, increased conductivity was clearly observed in all cases of feed solution containing foulants, and more so in the feed solution containing colloidal particles. Consequently, it may be concluded that the behavior of reversal salt selectivity and conductivity contributed to the interaction between the salt molecules and foulant in the ODMPs. Boo et al., (2012) reported that the confined back diffusion of salt changes the solution composition within the colloidal layer whereby becoming thicker and creating compact cake layers. Due to greater accumulation of salt near the membrane surface, this facilitated the increased salt concentration in the feed solution. However, accumulated salt molecules did not alter the properties of colloidal particle properties, but only increased the FO process osmotic pressure. By contrast, Xie et al., (2014) stated that a decrease in the reverse-draw salt (NaCl) flux also led to a decrease in the forward hydrogen ion flux. Besides that, the reverse flux of Cl^- was hindered by an enhanced electrostatic interaction with the more negatively charged HA fouling layer. The salt concentration of feed solution therefore, could be severely affected by the interaction of negatively charged HA fouling layer, thus contributing to the reversal salt selectivity as well as conductivity.

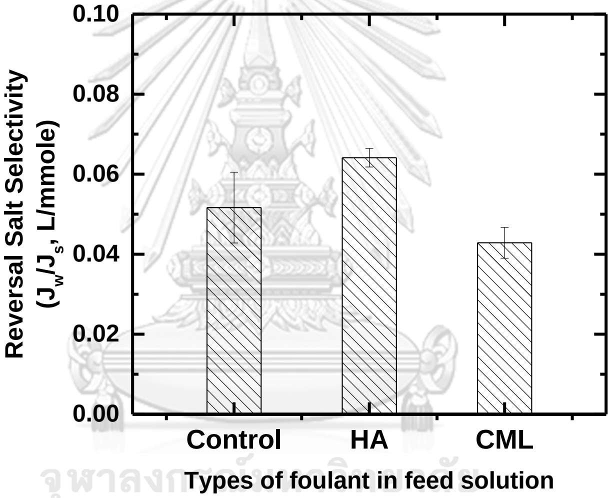


Figure 5.4 Reversal salt selectivity (J_w/J_s, L/mmole)

5.3.3 Impact of mixture surfactant containing HA, CML and Boron

To investigate the combination of surfactants for effluent, the effect of mixed-foulants on fouling of the osmotic membrane was investigated. Table 5.2 reveals the conditions of FO fouling experimentation.

Table 5.4 Data for FO run under different mixture and foulants

Condition	Active Layer		Supporting Layer		Flux in 8 h (LHM, average)
	NaCl (M)	π (atm)	NaCl (M)	π (atm)	
Mixture (1.0 CMC)	0.01	0.48	1.0	48.25	37.20
Mix+ 50 mg HA	0.01	0.48	1.0	48.25	38.85
Mix + 10^7/ml CML	0.01	0.48	1.0	48.25	36.05
Mix + 10 mg/l Boron	0.01	0.48	1.0	48.25	36.54

Figure 5.4 illustrates the influence on FO fouling experimentation by mixture (SDS+NP-40) in the presence of HA, CML, and boron as feed-foulant. Figure 5.4a exhibits that the normalized flux was least significant as compared with other combinations due to the deposition of mixed surfactant-humic acid which promoted the hydrophilicity on the osmotic membrane surface (Kaya et al., 2006, Li et al., 2011, Srisurichan et al., 2005). While the accumulation of mixed surfactant-colloidal particulates has more of an effect on the FO process due to the generated colloids layer on the osmotic membrane increase, the colloid-enhanced osmotic pressure (CEOP) of the FO system resulted in performance reduction. Additionally, the diffusion of salt molecules due to the covering of the foulant layer on the osmotic membrane surface was also continually investigated. The trend of observed salt flux in case of mixed surfactant-CML particulates at its highest diffusion is clearly shown in Figure 5.4b. This further elucidates the increase in salt concentration in the feed solution by the accumulated salt molecules near the osmotic surface. During operation of the FO system, the colloids would continually transfer into the membrane unit then attach to the osmotic membrane surface. The generated colloid-layers can promote the back diffusion of salt molecules from the feed solution to the draw solution, then, the concentration of salt molecules will

increase, thereby reducing the osmotic gradient pressure in the FO process. In case of mixed surfactant-boron with active-layer facing feed solution, the normalized flux decreased as clearly seen in Figure 5.4a. Moreover, the salt flux did not display any significant difference as compared with the others (Figure 5.4b). Furthermore, the effect of covering in mixed-foulant on reversal salt selectivity was investigated. Figure 54c indicates that reversal salt selectivity is highest when the feed solution is combined with surfactant-humic acid, followed by pure mixed surfactant and mixed-surfactant-boron, respectively. This result relates to the interaction between the properties of the osmotic membrane surface and the properties in humic acid molecules. At pH 7.0, the properties of the osmotic membrane surface are more negatively charged, and the functional groups of humic acid also dominate negatively charged as well as negatively charged combined surfactant. The diffusion of water molecules is increased when those foulants move into the FO system due to high hydrophilicity in the FO process. Contrariwise, with the combination of mixed-surfactant-colloids, reversal salt selectivity is decreased due to the increase in salt concentration in the feed solution as promoted by the CEOP. Therefore, the gradient osmotic pressure is reduced.

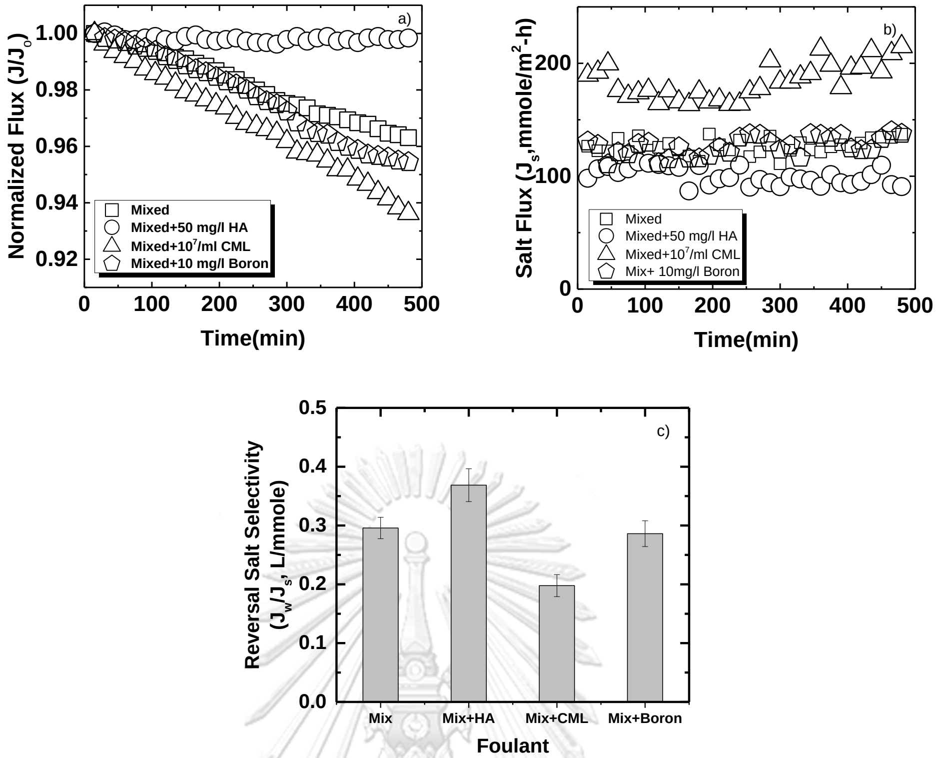


Figure 5.5 Influence of mixed-surfactant under different types of foulant

5.3.4 Chemical cleaning on fouled membrane

To study the effect of cleaning agents on the FO, DI, 1.0 M NaCl and pH 11 (NaOH) were used as cleaning agents amid FO experimentation. The fouled membrane was operated for 5 hrs, and the feed solution was prepared with 1.0 CMC mixture (SDS+NP-40), 50 mg/l HA, and 10 mg/l boron, respectively. Cleaning agent conditions are explicated in table 5.5.

Table 5.5 Data for FO run under different types of cleaning agent

Cleaning Agents	Active Layer		Supporting Layer	
	NaCl (M)	π (atm)	NaCl (M)	π (atm)
DI-water	0.00	0.00	1.0	48.25
0.1 M NaCl	0.10	4.80	1.0	48.25
NaOH (pH 12.0)	0.01	0.48	1.0	48.25

Table 5.4 illustrates the water flux and salt flux of fouled osmotic membrane by combination foulant types comprising of mixed-surfactant (SDS+NP-40), 50 mg/l HA, 10 mg/l boron, and 10^7/ml CML particulates. In case of DI-water as the cleaning agent, the averages of water flux in fouled osmotic membrane 26.95 L/m^2h and the salt flux were 971.30 mmole/m^2h, then, it is clearly observed that the water flux is increased to 30.25 L/m^2h and the salt flux is decreased to 587.14 mmole/m^2h when the DI-water is applied as cleaning agent. Normally, the osmotic membrane has a low generation foulant layer, meaning it is easy to clean the osmotic membrane surface. In the presence of NaCl (0.1 M), the water flux averages were 26.10 L/m^2h post performing for 5 hrs.20.99 L/m^2h of water flux in 0.1M NaCl was applied for the cleaning process. The reduction of water flux resultant of increased osmotic pressure at feed solution side can be explained in that the concentration/osmotic gradient pressure of the FO process decreased when the 0.1M NaCl was applied as cleaning agent. For NaOH (pH11) used for chemical cleaning, the water flux significantly increased from 26.53 to 31.84 L/m^2h (Table 5.3). As we were already aware, the solution would become more negatively charged when the NaOH was added to the solution. Once we applied the pH 11 (NaOH) to clean the osmotic membrane surface this resulted in the increasing of water flux due to greater negative charged on the osmotic membrane occurring which subsequently reduced the generated foulant layer. Furthermore, greater negative charged significantly promoted the diffusion of water molecules on the osmotic membrane surface.

Table 5.6 Efficiency of various chemical agents

Cleaning Agent	Water flux (L/m^{2}h)		Salt flux (mmole/m^{2}h)	
	Fouled (5hr)	cleaning	fouled(5hr)	cleaning
Virgin membrane	28.89		454.53	
DI-water	26.95	30.29	971.30	587.14
0.1 M NaCl	26.10	20.99	705.61	966.62
NaOH (pH 11.0)	26.53	31.84	399.57	105.61

For further observation, the behavior of flux decline and reversal salt selectivity was continually investigated as indicated in Figure 5.5. It was clearly discovered that the increased pH of solution (NaOH) improved the diffusion of water molecules and reversal salt selectivity amid the FO process (Figure 5.5a and 5.5b). On the other hand, the diffusion of salt molecules decreased due to elevated solution pH.

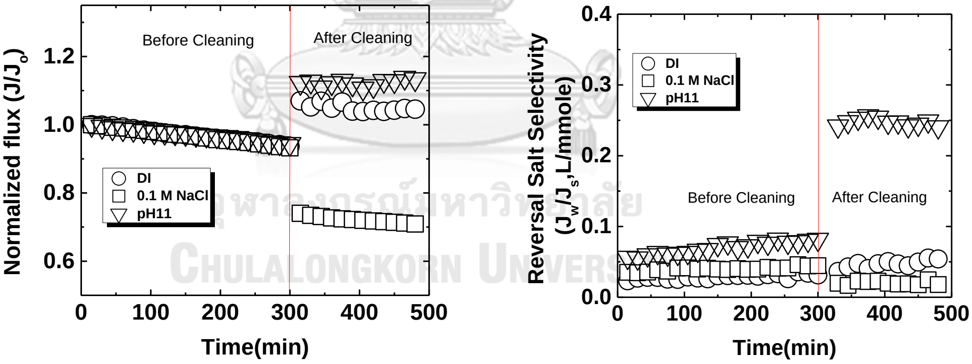


Figure 5.6 Influence of cleaning process under different types of agents

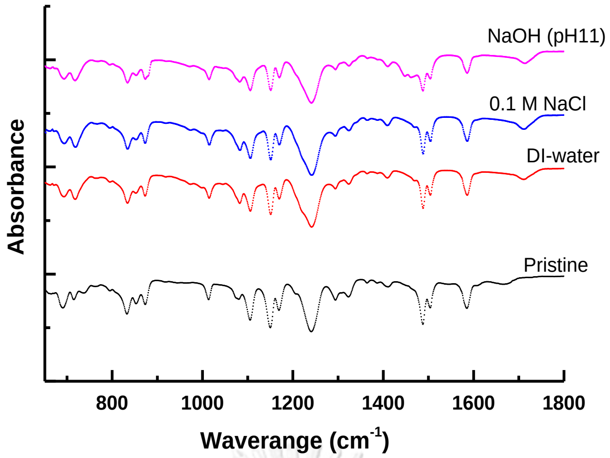


Figure 5.7 FTIR spectra of the pristine and surfactant-fouled by SDS, NP-40, and mixture surfactant

Post cleaning of foulant on the active layer of the osmotic membrane, the altered properties of the membrane surface occurred during operating due to the interaction between the foulants. Prior to analyzing the pristine membrane and fouled membrane, the functional group composition of the membrane surfaces was analyzed via FTIR spectra (Ang and Elimelech 2008). In this research, spectral ranges from 4000-450 cm^{-1} were applied to investigate the altered properties of both the pristine and fouled membranes. Figure 5.6 clearly exhibits FTIR spectrum profiles of a pristine as well as fouled membrane. Results indicated that the properties of the osmotic membrane did not display any significant IR peak post cleaning process due to functional groups on the active layer of the osmotic membrane not removing/changing in properties.

5.4 Conclusions

Process performance decreased when the FO system was operated under feed solution containing collodal particles (active layer) due to cake-enhanced osmotic pressure (CEOP) promoting reduced osmotic pressure gradient. Conversly, the feed solution containing HA molecules did not disturb the FO performance due to the coating of more negatively charged HA molecules successively reducing the hydrophobic of the membrane surface. Finally, in the case of mixture surfactant, the mixture surfactant containing HA molecules displayed less of an impact on FO performance due to greater hydrophilic from those mixture surfactants and HA molecules, resulting in the increase in diffusion of water molecules. For the cleaning process, the highest performance was increased when the FO system was operate at high pH (pH11) of feed solution, followed, DI-water, and 0.1 M NaCl, respectively.

CHAPTER VI
CONCLUSIONS

The investigations of this research afford an insight into the FO process. As a result, this study has facilitated a better understanding of the effect of single surfactant, combined surfactant, and combined surfactant with organic matter, colloidal particles, including cleaning process on the FO's performance. This chapter summarizes the new findings and recommends possible future work that can continuously extend this study. To be deeply understood the mechanism of membrane fouling in the FO process, this conclusion chapter is separately summarized as below:

Single surfactant fouling in FO process: the single surfactant molecules significantly increase the performance of FO process due to the adsorbed single surfactant on the active layer of osmotic membrane retards the flux decline. The hydrophobicity on the active layer of osmotic membrane would be increased due to the negatively charged of surfactant induced the diffusion of water molecules, whereby increasing FO performance. Contrariwise, the surfactant layer performing as a resistance on the osmotic membrane surface reduced the diffusion in salt molecules from the draw solution to feed solution, resulting in the reduction of salt flux. Interestingly, the reversal salt selectivity was rather stable even the FO process was run under different operating conditions.

Combined surfactant fouling in FO process: the performance of FO process seemed to be mainly dependent on the interactions between the osmotic membrane properties (active layer) and properties of surfactant. Furthermore, the findings was clearly indicated that these interactions are similar to the single surfactant reaction on the osmotic membrane surface; that is to say, the increasing in cross flow velocities retarded adsorption, and then increased the diffusion in water molecules. In addition, increased hydrophilic on the active layer due to the pH in feed solution being elevated, which thusly induced the diffusion of water molecules.

Cleaning agents in the FO process: it is easy to clean the osmotic membrane after operating under combined surfactant and others. The high recovery in cleaning of FO process was obviouly observed at high pH (pH 11, NaOH), followed, DI-water, and 0.1M NaCl, respectively. Due to more hydrophilic on the membrane surface reduced the adsorbed foulant molecules on the osmotic membrane surface. In additon, the properties of osmotic membrane surface (active layer) did not change in a functional groups.

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APPENDICES

APPENDIX A

Effect of osmotic pressure in draw solution

Table A-1 FO run under the concentration of draw concentration (0.1 M NaCl)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Concentration (NaCl, M)	0.01	0.5
Osmotic pressure (π, atm)	0.48	24.5
Flow rate, ml/min (cm/s)	235(7.03)	235(7.03)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w, (L/m^2-h)			J_s, (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0						
15	13.80	13.60	13.70	294.81	308.41	301.61
30	13.60	13.49	13.55	291.10	325.32	308.21
45	13.56	13.44	13.50	312.19	328.93	320.56
60	13.64	13.49	13.56	317.19	288.69	302.94
75	13.20	13.51	13.36	301.45	382.84	342.15
90	13.74	13.23	13.49	268.79	340.13	304.46

Table A-2 FO run under the concentration of draw concentration (0.5 M NaCl)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (**π**, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	235(7.03)	235(7.03)
pH of solution	7.0	7.0
Temperature, ^{o}C	25	25

Time	J_w, (L/m^2-h)			J_s, (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0						
15	24.92	24.96	24.94	484.84	457.63	471.23
30	24.80	24.66	24.73	421.16	486.47	453.82
45	24.74	24.94	24.84	451.05	467.46	459.26
60	24.86	24.89	24.88	429.76	478.82	454.29
75	24.26	24.80	24.53	473.56	465.01	469.29
90	24.36	24.71	24.54	418.04	420.50	419.27

Table A-3 FO run under the concentration of draw concentration (2.0 M NaCl)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Concentration (NaCl, M)	0.01	2.0
Osmotic pressure (π, atm)	0.48	97.8
Flow rate, ml/min (cm/s)	235(7.03)	235(7.03)
pH of solution	7.0	7.0
Temperature, ^{o}C	25	25

Time	J_w, (L/m^2-h)			J_s, (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0						
15	33.94	33.97	33.95	667.31	702.62	684.96
30	33.82	33.50	33.66	749.29	598.17	673.73
45	33.88	33.33	33.61	771.87	701.57	736.72
60	33.66	33.79	33.73	640.51	710.92	675.72
75	33.44	33.91	33.68	556.74	571.11	563.93
90	33.80	33.44	33.62	582.80	624.87	603.84

Table A-4 FO run under the concentration of draw concentration (3.0 M NaCl)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Concentration (NaCl, M)	0.01	3.0
Osmotic pressure (π, atm)	0.48	146.7
Flow rate, ml/min (cm/s)	235(7.03)	235(7.03)
pH of solution	7.0	7.0
Temperature, ^{o}C	25	25

Time	J_w, (L/m^2-h)			J_s, (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0						
15	44.70	44.78	44.74	829.09	875.32	852.21
30	44.66	44.14	44.40	903.46	927.35	915.40
45	44.50	44.52	44.51	878.91	907.04	892.98
60	44.62	44.27	44.45	868.23	950.88	909.56
75	44.66	44.64	44.65	913.00	864.24	888.62
90	44.34	44.32	44.33	960.20	931.42	945.81

Effect of cross-flow velocity in FO process

Table A-5 FO run under the flow rate (17.0 ml/min, 0.48 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	17.0(0.48)	17.0(0.48)
pH of solution	7.0	7.0
Temperature, ^{o}C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	13.56	13.52	13.54	243.85	274.00	258.92
30	13.48	13.52	13.50	272.28	274.54	273.41
45	13.46	13.50	13.48	254.22	253.72	253.97
60	13.40	13.52	13.46	250.50	258.52	254.51
120	13.42	13.52	13.47	265.10	262.90	264.00
180	13.40	13.48	13.44	241.04	253.88	247.46
240	13.40	13.50	13.45	269.11	261.05	265.08
300	13.38	13.44	13.41	277.15	252.89	265.02
360	13.36	13.50	13.43	262.99	269.16	266.08
420	13.38	13.50	13.44	243.22	250.52	246.87
480	13.36	13.44	13.40	275.11	242.53	258.82

Table A-6 FO run under the flow rate (33.0 ml/min, 0.92 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	33.0(0.92)	33.0(0.92)
pH of solution	7.0	7.0
Temperature, ^oC	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	19.42	19.53	19.48	327.80	384.42	356.11
30	19.14	19.51	19.33	373.24	364.84	369.04
45	19.10	19.47	19.29	363.03	333.35	348.19
60	19.28	19.53	19.41	357.02	362.11	359.56
120	19.02	19.49	19.26	370.54	351.22	360.88
180	19.00	19.51	19.26	409.68	366.63	388.15
240	19.06	19.47	19.27	349.36	369.58	359.47
300	19.04	19.39	19.22	391.22	365.14	378.18
360	19.08	19.45	19.27	342.79	353.38	348.09
420	18.92	19.39	19.16	358.93	373.52	366.22
480	18.98	19.37	19.18	382.94	343.20	363.07

Table A-7 FO run under the flow rate (253.0 ml/min, 7.03 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	24.62	23.96	24.29	484.98	457.63	471.30
30	24.80	23.66	24.23	421.37	486.47	453.92
45	23.74	23.94	23.84	451.26	467.46	459.36
60	23.86	23.89	23.88	429.99	478.82	454.40
120	23.54	23.74	23.64	431.42	446.17	438.80
180	23.50	23.16	23.33	474.17	467.38	470.77
240	23.58	23.80	23.69	479.74	491.56	485.65
300	23.50	23.67	23.58	411.61	463.13	437.37
360	23.14	23.92	23.53	436.90	473.67	455.29
420	23.98	23.68	23.83	493.70	436.41	465.05
480	23.18	23.26	23.22	464.86	479.92	472.39

Table A-8 FO run under the flow rate (380 ml/min, 10.5 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	380.0(10.5)	380.0(10.5)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	27.16	27.05	27.11	568.89	542.95	555.92
30	26.70	26.64	26.67	589.33	550.55	569.94
45	26.40	26.61	26.51	559.52	531.45	545.49
60	26.72	26.88	26.80	570.43	579.73	575.08
120	26.54	26.32	26.43	583.78	592.30	588.04
180	26.80	26.32	26.56	630.53	548.57	589.55
240	26.72	26.72	26.72	547.64	583.86	565.75
300	26.62	26.24	26.43	523.32	581.27	552.29
360	26.42	26.14	26.28	608.12	571.48	589.80
420	26.64	25.99	26.31	551.39	570.28	560.84
480	26.52	25.89	26.20	567.11	597.70	582.41

Effect of pH in feed solution

Table A-9 FO run under the pH of feed solution (at pH 4.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	4.0	7.0
Temperature, ^{o}C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	21.12	21.92	21.52	590.13	596.22	593.18
30	21.06	21.82	21.44	589.07	581.44	585.26
45	21.10	21.66	21.38	571.10	536.01	553.56
60	21.00	21.58	21.29	581.17	599.39	590.28
120	21.06	20.80	20.93	582.81	523.92	553.36
180	21.06	20.78	20.92	514.08	560.72	537.40
240	21.00	20.78	20.89	577.91	550.70	564.31
300	21.04	20.47	20.76	537.56	545.20	541.38
360	21.00	20.27	20.64	596.23	556.21	576.22
420	20.94	20.17	20.56	587.53	569.91	578.72
480	20.98	20.07	20.53	562.73	534.14	548.43

Table A-10 FO run under the pH of feed solution (at pH 6.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	6.0	7.0
Temperature, ^{o}C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	22.82	23.79	23.30	497.00	467.51	482.25
30	22.80	23.68	23.24	466.16	451.82	458.99
45	22.86	23.47	23.16	488.89	457.62	473.26
60	22.76	23.15	22.95	487.18	461.43	474.30
120	22.78	22.82	22.80	464.55	495.14	479.84
180	22.80	22.73	22.76	436.81	461.11	448.96
240	22.74	22.73	22.73	414.53	469.27	441.90
300	22.74	22.63	22.68	474.94	477.71	476.32
360	22.68	22.77	22.72	455.26	481.22	468.24
420	22.68	22.73	22.70	421.10	489.41	455.25
480	22.68	22.71	22.69	454.27	476.70	465.48

Table A-11 FO run under the pH of feed solution (at pH 7.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	22.82	23.79	23.30	497.00	467.51	482.25
30	22.80	23.68	23.24	466.16	451.82	458.99
45	22.86	23.47	23.16	488.89	457.62	473.26
60	22.76	23.15	22.95	487.18	461.43	474.30
120	22.78	22.82	22.80	464.55	495.14	479.84
180	22.80	22.73	22.76	436.81	461.11	448.96
240	22.74	22.73	22.73	414.53	469.27	441.90
300	22.74	22.63	22.68	474.94	477.71	476.32
360	22.68	22.77	22.72	455.26	481.22	468.24
420	22.68	22.73	22.70	421.10	489.41	455.25
480	22.68	22.71	22.69	454.27	476.70	465.48

Table A-12 FO run under the pH of feed solution (at pH 9.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	9.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	29.04	29.13	29.08	296.47	219.28	257.87
30	29.04	28.55	28.79	241.83	240.42	241.12
45	29.00	28.57	28.78	208.51	246.85	227.68
60	29.00	28.57	28.78	268.25	294.16	281.20
120	29.00	28.55	28.77	295.51	201.97	248.74
180	28.96	28.53	28.74	208.81	231.68	220.25
240	28.94	28.51	28.72	303.20	244.23	273.71
300	28.96	28.51	28.73	254.90	221.77	238.34
360	28.96	28.49	28.72	215.79	295.37	255.58
420	28.94	28.49	28.71	282.89	265.73	274.31
480	28.94	28.47	28.70	235.42	307.79	271.61

Table A-13 FO run under the pH of feed solution (at pH 10.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	10.0	7.0
Temperature, ^{o}C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	32.98	32.83	32.91	179.03	155.90	167.47
30	33.00	32.75	32.88	174.48	182.99	178.74
45	32.96	32.79	32.88	154.11	188.40	171.25
60	32.99	32.81	32.90	159.71	185.60	172.65
120	32.98	32.81	32.90	148.98	159.91	154.45
180	33.00	32.77	32.89	164.74	156.70	160.72
240	32.94	32.71	32.83	164.45	184.21	174.33
300	32.94	32.75	32.85	179.83	187.22	183.52
360	32.94	32.69	32.82	178.55	167.44	172.99
420	32.94	32.69	32.82	165.22	186.31	175.77
480	32.90	32.71	32.81	152.51	189.52	171.02

APPENDIX B

Effect of cross-flow velocity in FO process (feed containing SDS)

Table B-1 FO run under the flow rate (17.0 ml/min, 0.48 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
SDS concentration, g/l	2.37	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	17.0(0.48)	17.0(0.48)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	13.78	13.01	13.40	215.56	249.32	232.44
30	13.76	13.00	13.38	274.02	281.76	277.89
45	13.72	12.98	13.35	281.34	240.90	261.12
60	13.68	12.95	13.32	243.38	212.57	227.97
120	13.50	12.88	13.19	200.83	195.29	198.06
180	13.31	12.53	12.92	188.30	218.32	203.31
240	13.10	12.31	12.70	178.76	209.26	194.01
300	12.93	12.19	12.56	239.54	214.53	227.04
360	12.81	12.17	12.49	164.17	249.43	206.80
420	12.62	12.19	12.40	224.23	213.71	218.97
480	12.54	12.17	12.36	229.46	230.61	230.03

Table B-2 FO run under the flow rate (33.0 ml/min, 0.92 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
SDS concentration, g/l	2.37	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	33.0(0.92)	33.0(0.92)
pH of solution	7.0	7.0
Temperature, ^{o}C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	19.21	19.08	19.15	179.19	122.65	150.92
30	19.20	18.95	19.08	146.08	143.90	144.99
45	19.15	18.91	19.03	174.13	117.37	145.75
60	19.04	18.86	18.95	191.62	111.56	151.59
120	18.80	18.56	18.68	181.67	148.19	164.93
180	18.74	18.40	18.57	188.03	160.54	174.28
240	18.62	18.34	18.48	139.90	161.39	150.65
300	18.54	18.34	18.44	127.94	155.34	141.64
360	18.52	18.28	18.40	156.07	171.52	163.80
420	18.50	18.28	18.39	150.46	155.64	153.05
480	18.52	18.28	18.40	144.34	144.89	144.62

Table B-3 FO run under the flow rate (253.0 ml/min, 7.03 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
SDS concentration, g/l	2.37	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, ^{o}C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	33.60	32.67	33.13	56.01	98.60	77.31
30	33.44	32.64	33.04	107.33	70.81	89.07
45	33.35	32.52	32.93	97.69	76.69	87.19
60	33.28	32.46	32.87	68.56	76.65	72.60
120	33.04	32.52	32.78	110.63	81.40	96.01
180	32.94	32.38	32.66	109.86	71.82	90.84
240	32.82	32.30	32.56	106.05	96.11	101.08
300	32.76	32.22	32.49	92.26	90.84	91.55
360	32.60	32.20	32.40	95.37	93.94	94.65
420	32.54	32.16	32.35	93.96	108.40	101.18
480	32.50	32.16	32.33	99.65	95.13	97.39

Table B-4 FO run under the flow rate (380 ml/min, 10.5 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
SDS concentration, g/l	2.37	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	380.0(10.5)	380.0(10.5)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	37.45	36.96	37.20	155.55	177.55	166.55
30	37.16	36.69	36.92	238.68	164.52	201.60
45	37.14	36.57	36.85	174.72	206.66	190.69
60	37.14	36.47	36.81	136.62	226.03	181.33
75	37.10	36.41	36.75	218.17	119.95	169.06
90	37.10	36.37	36.73	144.04	132.64	138.34
105	37.08	36.37	36.72	172.02	136.79	154.41
120	37.08	36.33	36.70	126.89	182.84	154.86
135	37.08	36.31	36.69	104.65	136.28	120.46
150	37.08	36.31	36.69	124.83	136.39	130.61
165	37.04	36.23	36.63	177.45	115.51	146.48
180	37.04	36.23	36.63	136.78	183.48	160.13
195	36.98	36.15	36.56	110.75	185.85	148.30
210	36.96	36.15	36.55	151.64	132.39	142.02
225	37.00	36.11	36.55	188.44	146.00	167.22
240	36.96	36.09	36.52	190.08	140.10	165.09
255	36.94	36.07	36.50	178.34	191.38	184.86
270	36.92	36.03	36.47	103.04	169.59	136.32
285	36.92	36.03	36.47	139.66	127.45	133.55
300	36.88	36.01	36.44	179.93	147.61	163.77

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
315	36.84	35.97	36.41	136.70	193.93	165.31
330	36.84	35.93	36.39	139.58	176.89	158.24
345	36.80	35.91	36.36	152.93	122.61	137.77
360	36.80	35.89	36.35	142.62	122.55	132.59
375	36.78	35.91	36.35	155.07	102.81	128.94
390	36.80	35.93	36.37	178.95	112.91	145.93
405	36.76	35.89	36.33	117.13	132.30	124.72
420	36.76	35.88	36.32	144.42	123.38	133.90
435	36.74	35.89	36.32	137.35	168.98	153.16
450	36.72	35.83	36.28	151.94	149.85	150.89
465	36.70	35.87	36.29	144.48	123.65	134.06
480	36.70	35.85	36.28	147.01	112.48	129.74

Effect of pH in feed solution

Table B-5 FO run under the pH of feed solution (at pH 4.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
SDS concentration, g/l	2.37	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	4.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	29.00	28.16	28.58	126.391	159.863	143.127
30	28.87	27.85	28.36	114.404	218.413	166.408
45	28.80	27.79	28.29	212.576	210.389	211.483
60	28.72	27.59	28.16	137.288	139.160	138.224
75	28.64	27.52	28.08	154.602	210.659	182.630
90	28.58	27.47	28.03	216.202	156.956	186.579
105	28.49	27.43	27.96	144.079	90.100	117.090
120	28.42	27.43	27.93	128.924	151.110	140.017
135	28.35	27.41	27.88	185.362	131.020	158.191
150	28.29	27.39	27.84	104.741	118.597	111.669
165	28.20	27.39	27.80	80.461	140.581	110.521
180	28.16	27.33	27.75	94.234	179.123	136.679
195	28.08	27.30	27.69	126.232	109.558	117.895
210	28.10	27.32	27.71	191.140	137.410	164.275
225	28.06	27.30	27.68	110.392	95.188	102.790
240	28.04	27.28	27.66	131.357	112.421	121.889
255	28.04	27.28	27.66	96.151	119.455	107.803
270	28.04	27.24	27.64	98.270	93.054	95.662

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
285	28.00	27.22	27.61	116.502	124.981	120.742
300	28.00	27.22	27.61	106.603	120.584	113.594
315	28.00	27.16	27.58	131.316	157.835	144.575
330	27.96	27.16	27.56	144.230	158.120	151.175
345	27.96	27.12	27.54	185.870	125.842	155.856
360	27.90	27.06	27.48	90.634	84.282	87.458
375	27.94	27.06	27.50	143.059	83.477	113.268
390	27.92	27.04	27.48	142.860	121.588	132.224
405	27.90	27.06	27.48	85.715	97.515	91.615
420	27.90	27.00	27.45	182.983	117.634	150.309
435	27.88	27.02	27.45	206.529	109.139	157.834
450	27.88	27.02	27.45	211.054	131.923	171.489
465	27.90	27.00	27.45	89.937	165.819	127.878
480	27.90	27.02	27.46	147.930	181.604	164.767

Table B-6 FO run under the pH of feed solution (at pH 6.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
SDS concentration, g/l	2.37	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	6.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	22.82	23.79	23.30	110.98	167.79	139.38
30	22.80	23.68	23.24	117.32	101.34	109.33
45	22.86	23.47	23.16	102.25	142.91	122.58
60	22.76	23.15	22.95	133.81	113.30	123.56
75	22.70	23.07	22.88	101.40	149.25	125.33
90	22.80	22.87	22.83	111.37	104.51	107.94
105	22.72	22.77	22.74	140.03	144.44	142.24
120	22.78	22.82	22.80	107.75	108.45	108.10
135	22.76	22.79	22.77	135.28	95.78	115.53
150	22.76	22.75	22.75	104.42	126.71	115.57
165	22.78	22.75	22.76	110.54	145.68	128.11
180	22.80	22.73	22.76	106.35	101.87	104.11
195	22.74	22.73	22.73	109.26	140.97	125.12
210	22.76	22.75	22.75	86.55	139.85	113.20
225	22.76	22.71	22.73	111.49	108.70	110.09
240	22.74	22.73	22.73	100.67	132.64	116.66
255	22.76	22.61	22.69	102.51	101.74	102.12
270	22.72	22.63	22.68	103.37	124.30	113.83
285	22.72	22.65	22.68	99.43	91.76	95.59

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	22.74	22.63	22.68	103.69	97.79	100.74
315	22.70	22.57	22.64	114.82	119.48	117.15
330	22.72	22.58	22.65	119.44	146.62	133.03
345	22.70	22.75	22.72	81.55	102.16	91.85
360	22.68	22.77	22.72	171.26	81.19	126.23
375	22.70	22.59	22.65	80.04	120.44	100.24
390	22.70	22.73	22.71	87.13	112.11	99.62
405	22.66	22.71	22.68	131.17	91.08	111.13
420	22.68	22.73	22.70	138.95	145.82	142.39
435	22.66	22.71	22.68	106.34	123.48	114.91
450	22.68	22.73	22.70	155.63	107.05	131.34
465	22.66	22.73	22.69	102.31	109.97	106.14
480	22.68	22.71	22.69	155.91	147.57	151.74

Table B-7 FO run under the pH of feed solution (at pH 7.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
SDS concentration, g/l	2.37	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	33.60	32.67	33.13	56.01	98.60	77.31
30	33.44	32.64	33.04	107.33	70.81	89.07
45	33.35	32.52	32.93	97.69	76.69	87.19
60	33.28	32.46	32.87	68.56	76.65	72.60
75	33.21	32.38	32.79	80.08	67.94	74.01
90	33.18	32.38	32.78	107.82	79.10	93.46
105	33.10	32.52	32.81	73.74	94.21	83.98
120	33.04	32.52	32.78	110.63	81.40	96.01
135	33.00	32.46	32.73	81.88	91.17	86.52
150	33.00	32.46	32.73	80.25	69.04	74.65
165	32.96	32.40	32.68	80.61	63.12	71.87
180	32.94	32.38	32.66	109.86	71.82	90.84
195	32.90	32.38	32.64	73.76	102.33	88.05
210	32.90	32.34	32.62	95.41	103.15	99.28
225	32.86	32.34	32.60	71.33	89.26	80.30
240	32.82	32.30	32.56	106.05	96.11	101.08
255	32.80	32.30	32.55	93.59	84.67	89.13
270	32.78	32.28	32.53	90.52	83.54	87.03
285	32.76	32.24	32.50	94.76	90.87	92.81

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	32.76	32.22	32.49	92.26	90.84	91.55
315	32.72	32.16	32.44	87.69	90.32	89.01
330	32.68	32.14	32.41	71.63	95.01	83.32
345	32.60	32.16	32.38	98.55	100.24	99.39
360	32.60	32.20	32.40	95.37	93.94	94.65
375	32.58	32.18	32.38	91.03	99.45	95.24
390	32.58	32.14	32.36	93.85	94.46	94.16
405	32.56	32.16	32.36	91.71	95.71	93.71
420	32.54	32.16	32.35	93.96	108.40	101.18
435	32.50	32.16	32.33	107.74	92.88	100.31
450	32.50	32.16	32.33	98.91	97.70	98.31
465	32.50	32.16	32.33	98.41	91.81	95.11
480	32.50	32.16	32.33	99.65	95.13	97.39

Table B-8 FO run under the pH of feed solution (at pH 9.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
SDS concentration, g/l	2.37	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	9.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	35.70	34.60	35.15	86.86	105.01	95.94
30	35.68	34.54	35.11	128.29	108.13	118.21
45	35.64	34.54	35.09	120.99	114.91	117.95
60	35.60	34.52	35.06	122.49	107.92	115.21
75	35.60	34.50	35.05	115.53	98.95	107.24
90	35.56	34.46	35.01	104.90	107.14	106.02
105	35.56	34.44	35.00	104.40	98.34	101.37
120	35.48	34.38	34.93	94.95	124.68	109.82
135	35.48	34.34	34.91	96.12	100.54	98.33
150	35.44	34.30	34.87	100.06	112.24	106.15
165	35.44	34.26	34.85	109.09	113.39	111.24
180	35.38	34.24	34.81	131.06	127.49	129.28
195	35.36	34.22	34.79	93.22	106.32	99.77
210	35.30	34.16	34.73	107.41	98.34	102.88
225	35.22	34.14	34.68	92.40	106.83	99.62
240	35.22	34.10	34.66	90.08	97.95	94.02
255	35.16	34.10	34.63	108.57	93.41	100.99
270	35.12	34.06	34.59	89.63	110.32	99.98
285	35.02	34.04	34.53	84.08	109.76	96.92

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	35.02	34.02	34.52	98.23	123.79	111.01
315	35.02	33.99	34.50	108.63	101.99	105.31
330	34.96	33.97	34.46	119.09	98.22	108.66
345	34.94	33.95	34.44	113.78	105.66	109.72
360	34.90	33.93	34.41	89.63	118.53	104.08
375	34.82	33.91	34.36	102.16	121.54	111.85
390	34.80	33.87	34.33	118.84	95.06	106.95
405	34.80	33.83	34.31	102.18	120.48	111.33
420	34.78	33.77	34.27	118.87	104.26	111.56
435	34.78	33.75	34.26	94.74	94.10	94.42
450	34.76	33.75	34.25	91.98	129.05	110.52
465	34.76	33.75	34.25	111.76	105.46	108.61
480	34.74	33.77	34.25	95.84	102.99	99.41

Table B-9 FO run under the pH of feed solution (at pH 10.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
SDS concentration, g/l	2.37	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	10.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	37.90	36.82	37.36	157.65	114.87	136.26
30	37.89	36.80	37.35	133.10	107.46	120.28
45	37.84	36.76	37.30	138.69	106.54	122.62
60	37.84	36.70	37.27	126.55	118.89	122.72
75	37.81	36.65	37.23	107.08	122.12	114.60
90	37.80	36.55	37.17	98.30	122.24	110.27
105	37.80	36.51	37.15	134.38	96.16	115.27
120	37.76	36.45	37.10	86.99	135.70	111.34
135	37.74	36.37	37.05	140.22	90.77	115.50
150	37.74	36.35	37.04	103.51	142.63	123.07
165	37.70	36.29	36.99	118.88	133.64	126.26
180	37.68	36.23	36.95	91.90	119.45	105.68
195	37.64	36.17	36.90	159.20	127.67	143.44
210	37.64	36.13	36.88	151.87	90.47	121.17
225	37.60	36.09	36.84	106.12	88.26	97.19
240	37.60	36.05	36.82	127.53	82.12	104.83
255	37.60	35.99	36.80	90.18	85.23	87.71
270	37.56	35.93	36.75	112.25	109.91	111.08
285	37.54	35.89	36.72	94.02	145.84	119.93

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	37.52	35.85	36.69	82.32	108.04	95.18
315	37.48	35.81	36.65	100.51	123.73	112.12
330	37.46	35.75	36.61	109.68	143.45	126.56
345	37.44	35.69	36.57	125.41	98.67	112.04
360	37.40	35.67	36.54	126.51	95.14	110.82
375	37.36	35.63	36.50	123.04	114.56	118.80
390	37.36	35.57	36.47	120.67	145.05	132.86
405	37.28	35.49	36.39	115.13	93.49	104.31
420	37.24	35.41	36.33	121.60	102.02	111.81
435	37.20	35.35	36.28	113.11	146.94	130.02
450	37.20	35.30	36.25	120.07	110.88	115.47
465	37.20	35.24	36.22	129.06	148.65	138.86
480	37.18	35.18	36.18	169.63	106.20	137.92

Table B-10 FO run under the SDS concentration (SDS=0.273 g/l)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
SDS concentration, g/l	0.273	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	30.20	29.48	29.84	139.51	151.18	145.35
30	30.16	29.40	29.78	136.50	133.75	135.13
45	30.10	29.34	29.72	136.67	128.45	132.56
60	30.02	29.28	29.65	122.40	140.79	131.60
75	29.96	29.20	29.58	139.83	147.01	143.42
90	29.92	29.14	29.53	149.32	147.25	148.29
105	29.86	29.08	29.47	129.25	143.22	136.24
120	29.78	29.02	29.40	123.90	118.33	121.11
135	29.70	28.98	29.34	107.30	149.68	128.49
150	29.68	28.96	29.32	142.21	124.43	133.32
165	29.62	28.92	29.27	116.27	138.58	127.43
180	29.56	28.90	29.23	107.50	133.04	120.27
195	29.52	28.84	29.18	123.54	116.71	120.13
210	29.46	28.78	29.12	126.53	106.14	116.33
225	29.40	28.74	29.07	137.30	93.05	115.18
240	29.34	28.70	29.02	121.52	106.87	114.19
255	29.30	28.63	28.96	111.30	120.37	115.83
270	29.24	28.57	28.90	108.69	117.73	113.21
285	29.20	28.53	28.86	127.32	94.27	110.80

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	29.16	28.47	28.81	123.18	104.88	114.03
315	29.10	28.41	28.75	106.94	122.84	114.89
330	29.04	28.35	28.69	99.19	107.35	103.27
345	28.98	28.29	28.63	106.71	107.26	106.98
360	28.96	28.23	28.59	101.38	117.08	109.23
375	28.90	28.19	28.54	103.82	136.43	120.13
390	28.90	28.17	28.53	113.21	123.34	118.28
405	28.88	28.15	28.51	105.27	133.61	119.44
420	28.84	28.11	28.47	124.05	117.56	120.81
435	28.84	28.07	28.45	121.28	146.61	133.95
450	28.80	28.05	28.42	103.45	88.56	96.00
465	28.80	28.03	28.41	125.12	93.15	109.14
480	28.80	28.01	28.40	107.10	97.80	102.45

Table B-11 FO run under the SDS concentration (SDS=1.185 g/l)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
SDS concentration, g/l	1.185	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	30.60	30.54	30.57	120.15	142.70	131.42
30	30.59	30.50	30.54	134.28	104.12	119.20
45	30.54	30.47	30.51	128.40	122.60	125.50
60	30.50	30.44	30.47	140.33	138.78	139.55
75	30.45	30.40	30.43	110.98	109.46	110.22
90	30.40	30.37	30.39	119.37	124.13	121.75
105	30.36	30.33	30.35	127.41	138.34	132.88
120	30.34	30.23	30.29	124.75	133.44	129.09
135	30.30	30.15	30.23	110.42	114.97	112.70
150	30.24	30.07	30.16	102.05	108.38	105.21
165	30.20	30.01	30.11	152.26	123.50	137.88
180	30.16	29.98	30.07	112.50	115.22	113.86
195	30.08	29.94	30.01	141.55	109.68	125.61
210	30.00	29.86	29.93	143.26	100.63	121.94
225	29.96	29.78	29.87	116.24	92.54	104.39
240	29.92	29.76	29.84	177.19	113.59	145.39
255	29.86	29.70	29.78	146.83	118.38	132.60
270	29.80	29.66	29.73	133.05	133.34	133.19
285	29.76	29.62	29.69	95.07	105.52	100.30

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	29.70	29.58	29.64	92.13	124.09	108.11
315	29.62	29.54	29.58	103.43	97.43	100.43
330	29.52	29.48	29.50	143.65	107.25	125.45
345	29.48	29.44	29.46	109.05	149.23	129.14
360	29.46	29.42	29.44	109.20	107.99	108.60
375	29.43	29.38	29.40	93.66	127.82	110.74
390	29.40	29.34	29.37	98.25	140.19	119.22
405	29.38	29.30	29.34	113.40	138.28	125.84
420	29.36	29.26	29.31	100.80	135.96	118.38
435	29.33	29.24	29.29	141.47	121.79	131.63
450	29.32	29.16	29.24	139.05	110.97	125.01
465	29.30	29.08	29.19	151.07	132.76	141.92
480	29.28	29.04	29.16	127.37	117.02	122.19

Table B-12 FO run under the SDS concentration (SDS=2.73 g/l)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
SDS concentration, g/l	1.185	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	33.60	32.67	33.13	56.01	98.60	77.31
30	33.44	32.64	33.04	107.33	70.81	89.07
45	33.35	32.52	32.93	97.69	76.69	87.19
60	33.28	32.46	32.87	68.56	76.65	72.60
75	33.21	32.38	32.79	80.08	67.94	74.01
90	33.18	32.38	32.78	107.82	79.10	93.46
105	33.10	32.52	32.81	73.74	94.21	83.98
120	33.04	32.52	32.78	110.63	81.40	96.01
135	33.00	32.46	32.73	81.88	91.17	86.52
150	33.00	32.46	32.73	80.25	69.04	74.65
165	32.96	32.40	32.68	80.61	63.12	71.87
180	32.94	32.38	32.66	109.86	71.82	90.84
195	32.90	32.38	32.64	73.76	102.33	88.05
210	32.90	32.34	32.62	95.41	103.15	99.28
225	32.86	32.34	32.60	71.33	89.26	80.30
240	32.82	32.30	32.56	106.05	96.11	101.08
255	32.80	32.30	32.55	93.59	84.67	89.13
270	32.78	32.28	32.53	90.52	83.54	87.03
285	32.76	32.24	32.50	94.76	90.87	92.81

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	32.76	32.22	32.49	92.26	90.84	91.55
315	32.72	32.16	32.44	87.69	90.32	89.01
330	32.68	32.14	32.41	71.63	95.01	83.32
345	32.60	32.16	32.38	98.55	100.24	99.39
360	32.60	32.20	32.40	95.37	93.94	94.65
375	32.58	32.18	32.38	91.03	99.45	95.24
390	32.58	32.14	32.36	93.85	94.46	94.16
405	32.56	32.16	32.36	91.71	95.71	93.71
420	32.54	32.16	32.35	93.96	108.40	101.18
435	32.50	32.16	32.33	107.74	92.88	100.31
450	32.50	32.16	32.33	98.91	97.70	98.31
465	32.50	32.16	32.33	98.41	91.81	95.11
480	32.50	32.16	32.33	99.65	95.13	97.39

APPENDIX C

Effect of cross-flow velocity in FO process (feed containing NP-40)

Table C-1 FO run under the flow rate (17.0 ml/min, 0.48 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
NP-40 concentration, g/l	0.232	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	17.0(0.48)	17.0(0.48)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s ($mmole/m^2/h$)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	16.42	16.16	16.29	224.72	210.21	217.47
30	16.40	16.12	16.26	244.56	212.96	228.76
45	16.36	16.08	16.22	237.71	229.68	233.70
60	16.32	16.04	16.18	263.22	234.90	249.06
75	16.26	16.00	16.13	205.33	233.53	219.43
90	16.22	15.94	16.08	215.75	178.88	197.31
105	16.14	15.84	15.99	227.52	180.92	204.22
120	16.12	15.80	15.96	225.27	193.70	209.49
135	16.04	15.74	15.89	221.03	196.43	208.73
150	15.98	15.72	15.85	218.85	208.36	213.60
165	15.90	15.68	15.79	216.42	191.58	204.00
180	15.82	15.64	15.73	195.78	169.54	182.66
195	15.76	15.64	15.70	168.17	226.38	197.28
210	15.70	15.60	15.65	172.16	228.98	200.57
225	15.60	15.54	15.57	187.00	218.23	202.61
240	15.50	15.50	15.50	206.19	197.68	201.94
255	15.42	15.44	15.43	194.24	192.02	193.13
270	15.36	15.40	15.38	225.58	180.52	203.05

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
285	15.28	15.34	15.31	169.71	167.50	168.61
300	15.20	15.29	15.24	158.46	157.68	158.07
315	15.14	15.25	15.19	201.67	200.52	201.10
330	15.10	15.19	15.14	194.06	182.78	188.42
345	15.06	15.11	15.08	187.09	198.75	192.92
360	15.04	15.05	15.04	191.72	168.31	180.01
375	15.00	15.01	15.00	182.87	213.03	197.95
390	14.96	14.99	14.97	167.57	207.56	187.56
405	14.90	14.93	14.91	164.17	197.89	181.03
420	14.84	14.89	14.86	152.14	206.56	179.35
435	14.80	14.87	14.83	162.32	186.45	174.38
450	14.76	14.85	14.80	163.23	175.62	169.43
465	14.72	14.83	14.77	165.46	177.39	171.43
480	14.70	14.83	14.76	195.83	170.62	183.22

Table C-2 FO run under the flow rate (33.0 ml/min, 0.92 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
NP-40 concentration, g/l	0.232	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	33.0(0.92)	33.0(0.92)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	17.96	17.89	17.92	205.65	209.05	207.35
30	17.96	17.87	17.91	221.53	240.33	230.93
45	17.88	17.83	17.85	173.62	261.04	217.33
60	17.80	17.77	17.78	245.78	264.27	255.02
75	17.76	17.67	17.71	206.66	245.03	225.84
90	17.80	17.61	17.70	214.45	221.33	217.89
105	17.78	17.59	17.68	195.93	224.79	210.36
120	17.72	17.51	17.61	220.47	205.53	213.00
135	17.68	17.43	17.55	225.09	172.91	199.00
150	17.66	17.35	17.50	223.21	173.87	198.54
165	17.60	17.25	17.43	213.28	203.25	208.26
180	17.56	17.17	17.37	182.43	217.05	199.74
195	17.50	17.09	17.30	198.13	230.37	214.25
210	17.48	17.03	17.26	212.71	205.54	209.12
225	17.42	16.99	17.21	187.36	237.65	212.51
240	17.38	16.95	17.17	184.65	208.70	196.68
255	17.30	16.87	17.09	187.34	114.00	150.67
270	17.26	16.81	17.04	175.10	180.39	177.75
285	17.24	16.75	17.00	145.44	203.25	174.35

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	17.24	16.69	16.97	159.68	153.90	156.79
315	17.22	16.62	16.92	193.86	190.22	192.04
330	17.26	16.58	16.92	179.67	198.42	189.04
345	17.20	16.54	16.87	193.39	204.58	198.98
360	17.16	16.50	16.83	193.27	196.84	195.06
375	17.10	16.46	16.78	162.30	233.06	197.68
390	17.00	16.44	16.72	142.87	190.50	166.69
405	16.94	16.38	16.66	164.67	199.24	181.95
420	16.88	16.32	16.60	163.72	158.47	161.10
435	16.82	16.26	16.54	197.57	156.83	177.20
450	16.76	16.18	16.47	168.54	158.92	163.73
465	16.66	16.12	16.39	195.48	154.38	174.93
480	16.60	16.08	16.34	203.36	175.12	189.24

Table C-3 FO run under the flow rate (253.0 ml/min, 7.03 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
NP-40 concentration, g/l	0.232	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	26.52	25.77	26.14	221.95	247.80	234.88
30	26.48	25.73	26.10	232.43	218.00	225.22
45	26.46	25.71	26.08	214.04	205.88	209.96
60	26.42	25.67	26.04	224.96	211.59	218.28
75	26.40	25.63	26.01	222.08	202.24	212.16
90	26.38	25.61	25.99	223.29	189.54	206.41
105	26.34	25.57	25.95	213.98	174.75	194.36
120	26.32	25.55	25.93	190.68	189.09	189.89
135	26.28	25.51	25.89	170.97	194.87	182.92
150	26.22	25.47	25.84	192.80	195.12	193.96
165	26.18	25.45	25.81	208.76	207.63	208.19
180	26.16	25.39	25.77	194.34	186.17	190.26
195	26.12	25.35	25.73	165.46	197.15	181.31
210	26.10	25.33	25.72	189.28	182.31	185.79
225	26.04	25.27	25.66	195.59	171.30	183.44
240	26.00	25.23	25.62	190.25	150.43	170.34
255	25.98	25.17	25.58	178.20	143.69	160.94
270	25.94	25.11	25.53	171.46	154.39	162.93
285	25.92	25.03	25.48	154.68	153.46	154.07

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	25.90	24.97	25.44	140.31	159.05	149.68
315	25.84	24.93	25.39	175.56	164.19	169.88
330	25.78	24.89	25.34	160.01	157.75	158.88
345	25.76	24.79	25.28	154.76	166.68	160.72
360	25.70	24.73	25.22	139.38	169.69	154.53
375	25.66	24.66	25.16	129.09	167.28	148.19
390	25.60	24.56	25.08	143.76	150.56	147.16
405	25.56	24.50	25.03	138.72	139.10	138.91
420	25.52	24.48	25.00	137.96	145.13	141.55
435	25.48	24.42	24.95	134.95	154.49	144.72
450	25.46	24.40	24.93	137.53	147.39	142.46
465	25.44	24.36	24.90	148.49	120.78	134.63
480	25.42	24.30	24.86	148.53	118.10	133.31

Table C-4 FO run under the flow rate (380 ml/min, 10.5 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
NP-40 concentration, g/l	0.232	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	380.0(10.5)	380.0(10.5)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	30.84	29.52	30.18	229.85	218.01	223.93
30	30.80	29.46	30.13	234.27	217.35	225.81
45	30.76	29.40	30.08	213.55	196.28	204.91
60	30.72	29.34	30.03	207.10	206.94	207.02
75	30.68	29.26	29.97	190.19	216.16	203.17
90	30.60	29.18	29.89	229.31	203.47	216.39
105	30.58	29.12	29.85	237.77	216.17	226.97
120	30.56	29.08	29.82	238.50	209.77	224.14
135	30.52	29.02	29.77	192.16	233.88	213.02
150	30.46	28.96	29.71	151.37	178.24	164.81
165	30.42	28.88	29.65	129.59	183.48	156.54
180	30.38	28.78	29.58	180.90	167.65	174.27
195	30.36	28.74	29.55	176.90	180.73	178.82
210	30.32	28.67	29.49	172.68	173.98	173.33
225	30.28	28.65	29.46	180.06	170.49	175.27
240	30.24	28.59	29.41	164.75	199.55	182.15
255	30.22	28.53	29.37	206.61	181.86	194.23
270	30.20	28.43	29.31	187.76	163.79	175.77
285	30.16	28.39	29.27	149.30	151.74	150.52

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	30.10	28.33	29.21	151.74	150.77	151.25
315	30.02	28.27	29.14	101.20	155.38	128.29
330	30.00	28.19	29.09	125.50	153.75	139.63
345	29.96	28.11	29.03	115.75	167.18	141.47
360	29.92	28.07	28.99	180.77	133.78	157.28
375	29.86	28.05	28.95	162.93	141.65	152.29
390	29.80	27.99	28.90	148.41	127.75	138.08
405	29.74	27.93	28.84	128.64	152.27	140.46
420	29.68	27.89	28.79	129.70	109.84	119.77
435	29.64	27.85	28.75	124.43	116.41	120.42
450	29.58	27.79	28.69	128.20	114.27	121.23
465	29.50	27.77	28.64	115.52	119.30	117.41
480	29.48	27.75	28.62	104.61	131.55	118.08

Effect of pH in feed solution

Table C-5 FO run under the pH of feed solution (at pH 4.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
NP-40 concentration, g/l	0.232	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	4.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	18.42	17.61	18.01	325.305	332.607	328.956
30	18.40	17.57	17.98	332.208	341.588	336.898
45	18.36	17.53	17.94	310.506	344.464	327.485
60	18.32	17.47	17.89	335.028	329.498	332.263
75	18.26	17.43	17.84	328.893	358.955	343.924
90	18.20	17.37	17.78	333.162	364.502	348.832
105	18.14	17.31	17.73	298.795	349.475	324.135
120	18.08	17.27	17.68	292.412	360.807	326.610
135	18.04	17.23	17.64	296.278	345.870	321.074
150	18.00	17.15	17.58	319.499	322.490	320.994
165	17.94	17.11	17.53	327.366	319.463	323.414
180	17.90	17.05	17.48	255.741	339.345	297.543
195	17.82	17.03	17.43	258.952	330.415	294.684
210	17.74	16.99	17.37	276.336	310.265	293.301
225	17.66	16.95	17.31	279.287	279.076	279.182
240	17.60	16.89	17.25	282.147	270.777	276.462
255	17.52	16.87	17.20	287.781	265.295	276.538
270	17.44	16.83	17.14	293.315	271.021	282.168

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
285	17.38	16.77	17.08	301.496	298.833	300.165
300	17.32	16.73	17.03	290.162	304.149	297.155
315	17.26	16.69	16.98	284.471	284.666	284.569
330	17.20	16.67	16.94	278.836	306.346	292.591
345	17.14	16.64	16.89	292.353	289.676	291.015
360	17.10	16.62	16.86	275.739	286.689	281.214
375	17.04	16.58	16.81	287.752	278.370	283.061
390	17.00	16.56	16.78	256.488	288.852	272.670
405	16.98	16.52	16.75	269.754	261.848	265.801
420	16.92	16.48	16.70	248.269	267.062	257.665
435	16.88	16.44	16.66	242.921	251.028	246.975
450	16.82	16.42	16.62	242.952	240.395	241.674
465	16.78	16.36	16.57	229.777	235.235	232.506
480	16.72	16.30	16.51	229.885	277.033	253.459

Table C-6 FO run under the pH of feed solution (at pH 6.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
NP-40 concentration, g/l	0.232	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	6.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	20.24	19.57	19.91	224.24	252.26	238.25
30	20.22	19.53	19.88	259.84	279.60	269.72
45	20.20	19.49	19.85	220.00	244.67	232.34
60	20.16	19.43	19.80	214.71	235.68	225.20
75	20.12	19.39	19.76	218.36	239.15	228.76
90	20.08	19.35	19.72	192.15	229.95	211.05
105	20.02	19.32	19.67	179.82	224.35	202.09
120	20.00	19.26	19.63	217.23	234.77	226.00
135	19.94	19.24	19.59	221.56	243.24	232.40
150	19.88	19.22	19.55	220.01	232.61	226.31
165	19.80	19.18	19.49	200.67	240.40	220.54
180	19.76	19.12	19.44	185.58	241.52	213.55
195	19.70	19.08	19.39	186.06	219.12	202.59
210	19.68	19.02	19.35	194.11	203.81	198.96
225	19.62	19.00	19.31	191.63	226.42	209.02
240	19.56	18.94	19.25	177.42	230.61	204.01
255	19.52	18.92	19.22	216.53	228.84	222.69
270	19.48	18.88	19.18	225.66	228.47	227.07
285	19.42	18.82	19.12	201.87	231.94	216.91

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	19.36	18.78	19.07	198.97	208.59	203.78
315	19.32	18.72	19.02	202.60	203.49	203.05
330	19.30	18.70	19.00	176.04	198.38	187.21
345	19.24	18.66	18.95	192.51	215.63	204.07
360	19.16	18.62	18.89	163.70	213.09	188.39
375	19.14	18.60	18.87	166.42	198.83	182.63
390	19.06	18.52	18.79	172.88	196.51	184.69
405	19.00	18.50	18.75	166.00	190.14	178.07
420	18.98	18.44	18.71	152.57	186.01	169.29
435	18.94	18.42	18.68	152.67	172.21	162.44
450	18.90	18.38	18.64	177.38	178.56	177.97
465	18.88	18.32	18.60	174.79	203.33	189.06
480	18.82	18.28	18.55	146.91	172.65	159.78

Table C-7 FO run under the pH of feed solution (at pH 7.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
NP-40 concentration, g/l	0.232	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	26.52	25.77	26.14	221.95	247.80	234.88
30	26.48	25.73	26.10	232.43	218.00	225.22
45	26.46	25.71	26.08	214.04	205.88	209.96
60	26.42	25.67	26.04	224.96	211.59	218.28
75	26.40	25.63	26.01	222.08	202.24	212.16
90	26.38	25.61	25.99	223.29	189.54	206.41
105	26.34	25.57	25.95	213.98	174.75	194.36
120	26.32	25.55	25.93	190.68	189.09	189.89
135	26.28	25.51	25.89	170.97	194.87	182.92
150	26.22	25.47	25.84	192.80	195.12	193.96
165	26.18	25.45	25.81	208.76	207.63	208.19
180	26.16	25.39	25.77	194.34	186.17	190.26
195	26.12	25.35	25.73	165.46	197.15	181.31
210	26.10	25.33	25.72	189.28	182.31	185.79
225	26.04	25.27	25.66	195.59	171.30	183.44
240	26.00	25.23	25.62	190.25	150.43	170.34
255	25.98	25.17	25.58	178.20	143.69	160.94
270	25.94	25.11	25.53	171.46	154.39	162.93
285	25.92	25.03	25.48	154.68	153.46	154.07

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	25.90	24.97	25.44	140.31	159.05	149.68
315	25.84	24.93	25.39	175.56	164.19	169.88
330	25.78	24.89	25.34	160.01	157.75	158.88
345	25.76	24.79	25.28	154.76	166.68	160.72
360	25.70	24.73	25.22	139.38	169.69	154.53
375	25.66	24.66	25.16	129.09	167.28	148.19
390	25.60	24.56	25.08	143.76	150.56	147.16
405	25.56	24.50	25.03	138.72	139.10	138.91
420	25.52	24.48	25.00	137.96	145.13	141.55
435	25.48	24.42	24.95	134.95	154.49	144.72
450	25.46	24.40	24.93	137.53	147.39	142.46
465	25.44	24.36	24.90	148.49	120.78	134.63
480	25.42	24.30	24.86	148.53	118.10	133.31

Table C-8 FO run under the pH of feed solution (at pH 9.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
NP-40 concentration, g/l	0.232	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	9.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	25.70	26.00	25.85	163.73	130.47	147.10
30	25.66	25.99	25.82	128.83	137.60	133.22
45	25.62	25.95	25.78	158.67	140.72	149.69
60	25.60	25.91	25.75	173.97	144.03	159.00
75	25.58	25.89	25.73	171.56	138.77	155.16
90	25.54	25.83	25.68	178.81	153.02	165.92
105	25.50	25.81	25.65	157.42	166.64	162.03
120	25.48	25.75	25.61	151.11	169.09	160.10
135	25.44	25.73	25.58	140.32	169.44	154.88
150	25.40	25.69	25.54	144.78	147.18	145.98
165	25.36	25.63	25.49	155.06	142.16	148.61
180	25.34	25.61	25.47	149.91	156.64	153.28
195	25.30	25.55	25.42	147.90	148.72	148.31
210	25.28	25.53	25.40	146.98	162.82	154.90
225	25.24	25.49	25.36	139.19	165.71	152.45
240	25.22	25.43	25.32	132.04	149.57	140.80
255	25.20	25.41	25.30	150.21	149.80	150.00
270	25.16	25.37	25.26	138.89	110.54	124.72
285	25.14	25.31	25.23	130.43	118.43	124.43

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	25.08	25.29	25.19	139.13	115.03	127.08
315	25.04	25.21	25.13	149.95	115.90	132.92
330	25.02	25.19	25.11	150.00	132.70	141.35
345	24.98	25.15	25.07	137.04	136.00	136.52
360	24.94	25.09	25.02	132.05	131.04	131.55
375	24.92	25.07	25.00	132.21	138.75	135.48
390	24.90	25.03	24.97	154.86	133.71	144.28
405	24.86	25.01	24.94	144.49	128.74	136.61
420	24.80	24.97	24.89	107.56	126.50	117.03
435	24.76	24.95	24.86	144.94	137.16	141.05
450	24.74	24.89	24.82	143.29	122.63	132.96
465	24.70	24.87	24.79	146.56	146.27	146.41
480	24.66	24.83	24.75	124.47	138.68	131.57

Table C-9 FO run under the pH of feed solution (at pH 10.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
NP-40 concentration, g/l	0.232	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	10.0	7.0
Temperature, ^{o}C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	27.12	26.10	26.61	148.77	127.84	138.31
30	27.10	26.08	26.59	154.69	147.19	150.94
45	27.08	26.04	26.56	145.77	155.49	150.63
60	27.04	26.02	26.53	146.01	155.35	150.68
75	27.00	25.99	26.49	152.96	147.29	150.13
90	26.98	25.95	26.46	146.30	161.68	153.99
105	26.96	25.89	26.42	149.30	165.39	157.34
120	26.94	25.81	26.37	158.22	163.56	160.89
135	26.92	25.77	26.34	173.48	176.19	174.83
150	26.88	25.73	26.30	176.46	159.74	168.10
165	26.84	25.65	26.24	157.38	164.10	160.74
180	26.82	25.61	26.21	157.64	165.38	161.51
195	26.78	25.55	26.16	169.50	168.09	168.79
210	26.76	25.51	26.13	157.64	168.21	162.92
225	26.74	25.43	26.08	156.36	163.68	160.02
240	26.72	25.41	26.06	156.42	165.64	161.03
255	26.68	25.35	26.01	156.17	158.42	157.29
270	26.64	25.29	25.97	148.11	140.91	144.51
285	26.60	25.27	25.94	159.58	135.48	147.53

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	26.58	25.23	25.91	141.93	147.36	144.64
315	26.56	25.17	25.87	145.58	145.40	145.49
330	26.54	25.13	25.84	130.95	138.44	134.69
345	26.50	25.07	25.79	137.96	143.71	140.84
360	26.44	25.05	25.75	140.45	142.91	141.68
375	26.40	24.99	25.70	130.15	128.70	129.43
390	26.36	24.95	25.66	127.06	136.10	131.58
405	26.34	24.91	25.63	135.67	121.33	128.50
420	26.32	24.87	25.60	129.43	134.57	132.00
435	26.28	24.81	25.55	118.66	134.22	126.44
450	26.24	24.77	25.51	113.68	140.64	127.16
465	26.22	24.75	25.49	121.51	142.77	132.14
480	26.20	24.73	25.47	108.52	133.99	121.25

Table C-10 FO run under the NP-40 concentration (NP-40=0.02 g/l)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
NP-40 concentration, g/l	0.02	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, ^{o}C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	25.30	24.71	25.01	237.00	253.19	245.10
30	25.28	24.69	24.99	230.34	276.50	253.42
45	25.26	24.67	24.97	249.69	270.30	260.00
60	25.22	24.64	24.93	265.97	269.16	267.56
75	25.20	24.62	24.91	224.74	269.14	246.94
90	25.16	24.58	24.87	284.01	255.42	269.71
105	25.14	24.54	24.84	274.92	275.38	275.15
120	25.08	24.50	24.79	264.24	285.44	274.84
135	25.06	24.44	24.75	259.42	278.73	269.07
150	25.00	24.38	24.69	247.53	280.58	264.05
165	24.98	24.32	24.65	246.54	265.46	256.00
180	24.94	24.30	24.62	246.64	250.54	248.59
195	24.90	24.24	24.57	260.36	252.26	256.31
210	24.84	24.18	24.51	279.31	236.79	258.05
225	24.80	24.10	24.45	260.87	230.36	245.62
240	24.78	24.04	24.41	254.21	238.41	246.31
255	24.72	24.02	24.37	225.92	251.85	238.89
270	24.68	23.98	24.33	221.06	242.71	231.89
285	24.62	23.94	24.28	225.65	244.35	235.00

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	24.56	23.86	24.21	242.05	243.30	242.68
315	24.50	23.82	24.16	208.11	239.53	223.82
330	24.48	23.77	24.12	207.02	200.86	203.94
345	24.42	23.75	24.08	206.48	213.33	209.90
360	24.38	23.73	24.05	199.90	218.23	209.07
375	24.36	23.65	24.00	200.04	228.01	214.02
390	24.32	23.61	23.96	197.85	211.68	204.76
405	24.30	23.59	23.94	209.52	221.70	215.61
420	24.28	23.51	23.89	194.62	237.84	216.23
435	24.22	23.49	23.85	187.90	250.15	219.02
450	24.18	23.43	23.80	227.66	218.30	222.98
465	24.16	23.41	23.78	216.57	227.54	222.05
480	24.14	23.41	23.77	225.19	241.59	233.39

Table C-11 FO run under the NP-40 concentration (NP-40=0.116 g/l)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
NP-40 concentration, g/l	0.116	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	25.82	25.72	25.77	195.06	224.00	209.53
30	25.80	25.70	25.75	209.19	219.73	214.46
45	25.76	25.64	25.70	214.34	248.03	231.19
60	25.78	25.60	25.69	215.77	232.82	224.30
75	25.72	25.56	25.64	216.55	235.35	225.95
90	25.68	25.54	25.61	208.20	227.63	217.91
105	25.64	25.50	25.57	207.22	230.07	218.64
120	25.60	25.48	25.54	226.63	233.53	230.08
135	25.56	25.42	25.49	255.86	216.47	236.16
150	25.54	25.38	25.46	221.91	211.21	216.56
165	25.48	25.36	25.42	208.98	212.17	210.57
180	25.42	25.34	25.38	237.10	235.50	236.30
195	25.40	25.28	25.34	233.70	230.20	231.95
210	25.38	25.22	25.30	229.20	207.44	218.32
225	25.34	25.20	25.27	224.46	201.35	212.91
240	25.28	25.18	25.23	220.06	222.55	221.30
255	25.24	25.14	25.19	234.53	232.75	233.64
270	25.20	25.12	25.16	241.93	218.26	230.09
285	25.14	25.08	25.11	219.35	225.13	222.24

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	25.08	25.04	25.06	214.07	216.64	215.36
315	25.04	25.02	25.03	214.05	189.68	201.87
330	25.00	25.00	25.00	220.72	183.69	202.20
345	24.98	24.97	24.97	239.75	185.47	212.61
360	24.96	24.93	24.94	184.84	184.60	184.72
375	24.94	24.89	24.91	207.51	216.12	211.82
390	24.88	24.83	24.85	208.02	220.29	214.15
405	24.82	24.75	24.78	208.39	217.01	212.70
420	24.80	24.73	24.76	188.65	228.35	208.50
435	24.74	24.69	24.71	177.13	212.55	194.84
450	24.70	24.63	24.66	196.54	206.86	201.70
465	24.68	24.61	24.64	175.65	195.95	185.80
480	24.66	24.61	24.63	172.95	196.61	184.78

Table C-12 FO run under the NP-40 concentration (NP-40=0.232 g/l)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
NP-40 concentration, g/l	0.232	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	26.49	25.74	26.12	181.95	207.80	194.88
30	26.48	25.73	26.10	202.43	218.00	210.22
45	26.46	25.71	26.08	214.04	205.88	209.96
60	26.42	25.69	26.05	204.96	211.59	208.28
75	26.40	25.65	26.03	222.08	202.24	212.16
90	26.38	25.62	26.00	223.29	189.54	206.41
105	26.34	25.60	25.97	213.98	174.75	194.36
120	26.32	25.56	25.94	190.68	189.09	189.89
135	26.28	25.54	25.91	170.97	194.87	182.92
150	26.22	25.52	25.87	192.80	195.12	193.96
165	26.18	25.49	25.84	208.76	207.63	208.19
180	26.16	25.46	25.81	194.34	186.17	190.26
195	26.12	25.41	25.77	165.46	197.15	181.31
210	26.10	25.39	25.75	189.28	182.31	185.79
225	26.04	25.37	25.71	195.59	171.30	183.44
240	26.00	25.33	25.67	190.25	150.43	170.34
255	25.98	25.30	25.64	178.20	143.69	160.94
270	25.94	25.28	25.61	171.46	154.39	162.93
285	25.92	25.25	25.59	154.68	153.46	154.07

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	25.90	25.22	25.56	140.31	159.05	149.68
315	25.84	25.20	25.52	175.56	164.19	169.88
330	25.78	25.18	25.48	160.01	157.75	158.88
345	25.76	25.14	25.45	154.76	166.68	160.72
360	25.70	25.09	25.39	139.38	169.69	154.53
375	25.66	25.03	25.34	129.09	167.28	148.19
390	25.60	25.00	25.30	143.76	150.56	147.16
405	25.56	24.98	25.27	138.72	139.10	138.91
420	25.52	24.95	25.24	137.96	145.13	141.55
435	25.48	24.91	25.20	134.95	154.49	144.72
450	25.46	24.88	25.17	137.53	147.39	142.46
465	25.44	24.85	25.14	148.49	120.78	134.63
480	25.42	24.81	25.12	148.53	148.10	148.31

APENDIX D

Effect of cross-flow velocity in FO process (feed containing combination)

Table D-1 FO run under the flow rate (17.0 ml/min, 0.48 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Mix concentration	1.0 CMC	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	17.0(0.48)	17.0(0.48)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	26.48	26.62	26.55	132.19	177.06	154.62
30	26.44	26.60	26.52	145.50	174.24	159.87
45	26.42	26.56	26.49	141.61	164.96	153.28
60	26.40	26.54	26.47	114.59	151.96	133.27
75	26.36	26.48	26.42	118.48	161.99	140.23
90	26.30	26.42	26.36	142.72	156.71	149.71
105	26.28	26.40	26.34	166.37	145.10	155.73
120	26.22	26.34	26.28	134.83	149.16	142.00
135	26.14	26.32	26.23	138.82	132.05	135.44
150	26.12	26.28	26.20	138.90	133.30	136.10
165	26.08	26.24	26.16	149.40	138.11	143.76
180	26.04	26.18	26.11	138.07	138.65	138.36
195	26.00	26.14	26.07	147.22	144.88	146.05
210	25.96	26.08	26.02	129.08	144.67	136.87
225	25.92	26.02	25.97	124.71	154.20	139.45
240	25.84	25.97	25.90	125.90	124.90	125.40
255	25.74	25.87	25.80	116.27	132.95	124.61
270	25.68	25.81	25.74	128.99	131.67	130.33

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
285	25.62	25.75	25.68	114.76	142.24	128.50
300	25.56	25.71	25.63	115.59	111.53	113.56
315	25.48	25.67	25.57	104.61	103.95	104.28
330	25.46	25.61	25.53	110.88	104.02	107.45
345	25.40	25.53	25.46	119.90	112.76	116.33
360	25.36	25.49	25.42	117.59	108.19	112.89
375	25.32	25.41	25.36	94.91	108.32	101.61
390	25.26	25.29	25.28	103.83	108.50	106.17
405	25.22	25.23	25.23	133.14	105.58	119.36
420	25.20	25.21	25.21	104.00	128.57	116.28
435	25.16	25.11	25.14	94.11	128.50	111.30
450	25.14	25.07	25.11	101.50	133.14	117.32
465	25.12	25.01	25.07	93.83	131.65	112.74
480	25.06	25.01	25.04	102.78	115.95	109.36

Table D-2 FO run under the flow rate (33.0 ml/min, 0.92 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Mix concentration	1.0 CMC	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	33.0(0.92)	33.0(0.92)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	29.12	28.03	28.57	158.87	135.67	147.27
30	29.04	28.01	28.52	150.11	143.45	146.78
45	29.00	27.95	28.48	159.28	148.53	153.91
60	28.98	27.87	28.43	168.16	147.37	157.77
75	28.96	27.79	28.38	167.99	125.97	146.98
90	28.88	27.75	28.32	173.68	168.25	170.96
105	28.82	27.71	28.27	161.83	162.33	162.08
120	28.76	27.61	28.19	147.32	156.59	151.95
135	28.74	27.53	28.14	147.22	162.19	154.71
150	28.70	27.51	28.11	169.66	139.45	154.56
165	28.66	27.41	28.04	158.35	146.80	152.58
180	28.60	27.39	28.00	157.72	153.36	155.54
195	28.58	27.35	27.97	162.72	147.58	155.15
210	28.54	27.32	27.93	121.10	150.03	135.56
225	28.48	27.24	27.86	163.49	152.45	157.97
240	28.40	27.20	27.80	165.19	152.00	158.59
255	28.36	27.14	27.75	162.67	130.24	146.46
270	28.32	27.06	27.69	137.08	124.82	130.95
285	28.26	27.00	27.63	157.34	150.86	154.10

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	28.00	26.98	27.49	132.34	157.95	145.14
315	27.96	26.94	27.45	136.04	162.26	149.15
330	27.90	26.84	27.37	130.78	146.08	138.43
345	27.82	26.80	27.31	168.34	150.38	159.36
360	27.74	26.76	27.25	144.42	141.91	143.16
375	27.66	26.74	27.20	133.53	143.50	138.52
390	27.60	26.72	27.16	140.62	127.64	134.13
405	27.48	26.66	27.07	157.65	122.02	139.83
420	27.42	26.60	27.01	144.78	138.42	141.60
435	27.40	26.56	26.98	131.37	138.02	134.70
450	27.34	26.50	26.92	122.63	136.47	129.55
465	27.30	26.48	26.89	128.71	151.97	140.34
480	27.20	26.44	26.82	122.98	148.96	135.97

Table D-3 FO run under the flow rate (253.0 ml/min, 7.03 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Mix concentration	1.0 CMC	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, ^{o}C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	37.89	39.99	38.94	126.11	120.04	123.07
30	37.88	39.96	38.92	101.81	115.42	108.62
45	37.86	39.90	38.88	101.44	110.77	106.10
60	37.82	39.86	38.84	122.45	103.19	112.82
75	37.80	39.78	38.79	108.65	110.55	109.60
90	37.76	39.72	38.74	104.37	102.11	103.24
105	37.70	39.70	38.70	121.53	111.65	116.59
120	37.64	39.64	38.64	124.04	116.85	120.44
135	37.58	39.58	38.58	127.24	120.37	123.81
150	37.56	39.54	38.55	102.13	120.35	111.24
165	37.50	39.50	38.50	115.83	107.58	111.71
180	37.46	39.42	38.44	121.09	107.39	114.24
195	37.40	39.36	38.38	115.06	121.47	118.27
210	37.34	39.31	38.32	115.45	103.41	109.43
225	37.28	39.27	38.27	100.80	99.47	100.14
240	37.20	39.21	38.20	99.35	117.20	108.27
255	37.14	39.13	38.13	104.78	108.52	106.65
270	37.08	39.11	38.09	98.94	107.30	103.12
285	37.00	39.05	38.02	112.91	98.76	105.83

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	36.96	39.01	37.98	108.21	112.44	110.32
315	36.94	38.97	37.95	109.69	95.86	102.77
330	36.90	38.91	37.90	106.36	114.36	110.36
345	36.82	38.87	37.84	109.95	101.77	105.86
360	36.80	38.79	37.79	117.73	98.69	108.21
375	36.78	38.71	37.74	102.10	99.97	101.03
390	36.74	38.67	37.70	103.81	112.57	108.19
405	36.70	38.65	37.68	101.84	107.04	104.44
420	36.68	38.61	37.65	114.60	97.76	106.18
435	36.62	38.55	37.59	99.15	109.20	104.18
450	36.56	38.51	37.54	109.48	105.19	107.34
465	36.54	38.49	37.52	108.61	104.07	106.34
480	36.50	38.45	37.48	101.26	100.79	101.02

Table D-4 FO run under the flow rate (380 ml/min, 10.5 cm/s)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Mix concentration	1.0 CMC	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	380.0(10.5)	380.0(10.5)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	44.32	44.74	44.53	131.84	117.71	124.78
30	44.28	44.70	44.49	148.14	92.72	120.43
45	44.20	44.67	44.43	140.30	100.51	120.40
60	44.14	44.63	44.38	118.00	96.38	107.19
75	44.12	44.57	44.34	116.35	100.83	108.59
90	44.10	44.49	44.29	120.28	105.03	112.65
105	44.02	44.47	44.24	95.98	108.81	102.39
120	44.00	44.43	44.21	106.13	106.84	106.48
135	43.96	44.39	44.17	95.69	102.06	98.88
150	43.92	44.29	44.10	110.17	124.21	117.19
165	43.84	44.27	44.05	102.67	118.74	110.70
180	43.78	44.21	43.99	109.96	84.63	97.29
195	43.72	44.13	43.92	95.79	92.00	93.90
210	43.64	44.07	43.85	105.57	105.31	105.44
225	43.58	44.03	43.80	98.60	96.26	97.43
240	43.50	43.99	43.75	111.74	99.26	105.50
255	43.48	43.89	43.69	119.49	97.64	108.56
270	43.42	43.83	43.63	120.88	107.57	114.23
285	43.40	43.79	43.60	93.76	95.55	94.65

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	43.34	43.75	43.55	98.27	83.83	91.05
315	43.26	43.69	43.48	100.75	90.16	95.46
330	43.20	43.67	43.44	102.52	83.62	93.07
345	43.16	43.63	43.40	110.32	112.76	111.54
360	43.12	43.59	43.36	117.93	117.67	117.80
375	43.08	43.55	43.32	111.65	84.77	98.21
390	43.04	43.47	43.26	118.53	95.99	107.26
405	43.00	43.41	43.21	112.06	100.13	106.10
420	42.98	43.30	43.14	99.86	95.76	97.81
435	42.94	43.28	43.11	107.62	103.13	105.38
450	42.86	43.22	43.04	128.21	86.58	107.39
465	42.84	43.16	43.00	127.17	93.70	110.44
480	42.80	43.12	42.96	115.90	84.56	100.23

Effect of pH in feed solution

Table D-5 FO run under the pH of feed solution (at pH 4.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Mix concentration	1.0 CMC	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	4.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	27.09	26.92	27.00	166.03	178.97	172.50
30	26.96	26.88	26.92	163.49	167.30	165.40
45	26.82	26.86	26.84	160.96	158.76	159.86
60	26.80	26.80	26.80	144.04	165.06	154.55
75	26.76	26.76	26.76	150.32	156.59	153.45
90	26.70	26.70	26.70	147.91	148.27	148.09
105	26.64	26.64	26.64	178.97	134.33	156.65
120	26.60	26.60	26.60	170.19	133.48	151.84
135	26.54	26.58	26.56	148.71	152.91	150.81
150	26.48	26.50	26.49	149.05	127.80	138.42
165	26.44	26.46	26.45	135.22	145.08	140.15
180	26.36	26.40	26.38	163.65	145.33	154.49
195	26.30	26.38	26.34	158.63	131.69	145.16
210	26.24	26.32	26.28	138.58	132.03	135.31
225	26.18	26.28	26.23	130.61	132.29	131.45
240	26.16	26.22	26.19	139.01	143.31	141.16
255	26.12	26.14	26.13	139.11	127.32	133.22

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
270	26.08	26.08	26.08	120.52	135.50	128.01
285	26.00	26.04	26.02	135.45	130.24	132.85
300	25.98	25.98	25.98	125.16	138.50	131.83
315	25.94	25.88	25.91	139.39	138.39	138.89
330	25.88	25.81	25.84	139.15	130.53	134.84
345	25.82	25.65	25.73	128.98	135.59	132.28
360	25.80	25.61	25.70	139.38	130.29	134.84
375	25.76	25.57	25.66	129.22	147.50	138.36
390	25.72	25.53	25.62	139.16	134.95	137.05
405	25.68	25.49	25.58	122.03	159.92	140.97
420	25.62	25.43	25.52	141.88	132.54	137.21
435	25.60	25.41	25.50	131.89	137.64	134.76
450	25.56	25.37	25.46	129.45	127.36	128.41
465	25.54	25.35	25.44	134.24	125.14	129.69
480	25.44	25.25	25.35	142.24	132.42	137.33

Table D-6 FO run under the pH of feed solution (at pH 6.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Mix concentration	1.0 CMC	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	6.0	7.0
Temperature, ^{o}C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	29.70	28.42	29.06	154.09	153.45	153.77
30	29.68	28.41	29.04	164.21	153.29	158.75
45	29.62	28.39	29.00	150.27	158.26	154.27
60	29.60	28.35	28.97	158.38	157.66	158.02
75	29.58	28.27	28.92	155.48	152.05	153.77
90	29.56	28.21	28.88	170.01	146.49	158.25
105	29.53	28.17	28.85	159.81	146.71	153.26
120	29.42	28.15	28.78	163.81	138.31	151.06
135	29.40	28.07	28.73	157.88	144.24	151.06
150	29.36	28.01	28.68	152.09	138.76	145.42
165	29.20	27.95	28.58	146.32	130.56	138.44
180	29.18	27.91	28.55	146.11	144.55	145.33
195	29.14	27.83	28.49	148.61	139.06	143.83
210	29.10	27.79	28.45	129.17	147.16	138.17
225	29.02	27.73	28.38	134.55	146.96	140.76
240	28.96	27.69	28.33	123.61	144.00	133.81
255	28.88	27.61	28.25	128.88	138.46	133.67
270	28.82	27.53	28.18	131.29	135.64	133.46
285	28.80	27.47	28.14	115.18	111.88	113.53

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	28.76	27.41	28.09	112.41	114.55	113.48
315	28.74	27.32	28.03	119.91	119.76	119.83
330	28.68	27.28	27.98	132.33	119.57	125.95
345	28.60	27.20	27.90	131.76	124.48	128.12
360	28.58	27.16	27.87	151.08	104.02	127.55
375	28.54	27.08	27.81	140.02	108.99	124.50
390	28.50	27.00	27.75	134.09	103.90	119.00
405	28.42	26.96	27.69	138.10	111.04	124.57
420	28.40	26.90	27.65	122.42	105.85	114.13
435	28.38	26.82	27.60	125.06	118.00	121.53
450	28.32	26.76	27.54	129.37	127.60	128.49
465	28.28	26.68	27.48	116.38	113.01	114.69
480	28.24	26.65	27.45	116.07	112.75	114.41

Table D-7 FO run under the pH of feed solution (at pH 7.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Mix concentration	1.0 CMC	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	37.89	39.99	38.94	126.11	120.04	123.07
30	37.88	39.96	38.92	101.81	115.42	108.62
45	37.86	39.90	38.88	101.44	110.77	106.10
60	37.82	39.86	38.84	122.45	103.19	112.82
75	37.80	39.78	38.79	108.65	110.55	109.60
90	37.76	39.72	38.74	104.37	102.11	103.24
105	37.70	39.70	38.70	121.53	111.65	116.59
120	37.64	39.64	38.64	124.04	116.85	120.44
135	37.58	39.58	38.58	127.24	120.37	123.81
150	37.56	39.54	38.55	102.13	120.35	111.24
165	37.50	39.50	38.50	115.83	107.58	111.71
180	37.46	39.42	38.44	121.09	107.39	114.24
195	37.40	39.36	38.38	115.06	121.47	118.27
210	37.34	39.31	38.32	115.45	103.41	109.43
225	37.28	39.27	38.27	100.80	99.47	100.14
240	37.20	39.21	38.20	99.35	117.20	108.27
255	37.14	39.13	38.13	104.78	108.52	106.65
270	37.08	39.11	38.09	98.94	107.30	103.12
285	37.00	39.05	38.02	112.91	98.76	105.83

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	36.96	39.01	37.98	108.21	112.44	110.32
315	36.94	38.97	37.95	109.69	95.86	102.77
330	36.90	38.91	37.90	106.36	114.36	110.36
345	36.82	38.87	37.84	109.95	101.77	105.86
360	36.80	38.79	37.79	117.73	98.69	108.21
375	36.78	38.71	37.74	102.10	99.97	101.03
390	36.74	38.67	37.70	103.81	112.57	108.19
405	36.70	38.65	37.68	101.84	107.04	104.44
420	36.68	38.61	37.65	114.60	97.76	106.18
435	36.62	38.55	37.59	99.15	109.20	104.18
450	36.56	38.51	37.54	109.48	105.19	107.34
465	36.54	38.49	37.52	108.61	104.07	106.34
480	36.50	38.45	37.48	101.26	100.79	101.02

Table D-8 FO run under the pH of feed solution (at pH 9.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Mix concentration	1.0 CMC	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	9.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	35.67	34.36	35.01	67.51	68.92	68.21
30	35.65	34.34	34.99	64.29	53.91	59.10
45	35.64	34.33	34.98	61.90	67.80	64.85
60	35.60	34.30	34.95	57.84	67.41	62.63
75	35.52	34.26	34.89	62.93	58.11	60.52
90	35.48	34.21	34.85	66.63	65.93	66.28
105	35.44	34.19	34.82	67.44	54.95	61.19
120	35.41	34.17	34.79	70.88	54.43	62.65
135	35.40	34.15	34.77	68.15	59.69	63.92
150	35.38	34.11	34.74	67.77	57.80	62.78
165	35.32	34.08	34.70	64.66	71.37	68.02
180	35.26	34.02	34.64	64.20	68.51	66.36
195	35.10	34.01	34.55	65.58	60.95	63.27
210	35.07	33.95	34.51	55.98	62.51	59.24
225	35.04	33.92	34.48	66.12	61.49	63.81
240	34.96	33.87	34.42	68.85	63.15	66.00
255	34.95	33.83	34.39	60.82	68.47	64.65
270	34.92	33.81	34.36	68.68	52.66	60.67

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
285	34.89	33.79	34.34	58.89	63.15	61.02
300	34.86	33.75	34.31	66.61	74.38	70.49
315	34.84	33.69	34.27	64.16	61.20	62.68
330	34.82	33.64	34.23	61.71	69.15	65.43
345	34.81	33.58	34.19	55.11	61.96	58.54
360	34.78	33.50	34.14	67.35	76.73	72.04
375	34.75	33.40	34.07	62.36	74.19	68.27
390	34.74	33.36	34.05	69.45	58.48	63.97
405	34.70	33.30	34.00	68.81	61.36	65.09
420	34.68	33.24	33.96	58.89	73.92	66.40
435	34.66	33.16	33.91	89.45	65.02	77.23
450	34.64	33.14	33.89	94.99	59.41	77.20
465	34.60	33.12	33.86	75.24	61.49	68.36
480	34.58	33.10	33.84	77.17	56.05	66.61

Table D-9 FO run under the pH of feed solution (at pH 10.0)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Mix concentration	1.0 CMC	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	10.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	42.10	40.45	41.28	47.77	50.55	49.16
30	42.08	40.44	41.26	57.76	54.60	56.18
45	42.02	40.36	41.19	67.82	53.38	60.60
60	42.00	40.30	41.15	58.28	50.17	54.22
75	41.96	40.24	41.10	54.97	54.10	54.54
90	41.92	40.16	41.04	51.77	49.53	50.65
105	41.86	40.08	40.97	58.63	54.23	56.43
120	41.80	40.04	40.92	55.49	50.10	52.80
135	41.74	40.01	40.87	45.12	53.02	49.07
150	41.70	39.98	40.84	61.87	47.69	54.78
165	41.62	39.95	40.78	48.75	51.90	50.33
180	41.60	39.91	40.75	52.80	60.85	56.83
195	41.54	39.89	40.71	47.07	55.15	51.11
210	41.48	39.89	40.68	49.31	49.91	49.61
225	41.40	39.83	40.62	54.02	44.60	49.31
240	41.38	39.80	40.59	49.19	54.01	51.60
255	41.34	39.76	40.55	53.58	54.20	53.89
270	41.26	39.74	40.50	57.30	58.53	57.92
285	41.22	39.73	40.47	58.34	53.53	55.93

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	41.20	39.71	40.46	51.53	50.08	50.81
315	41.16	39.68	40.42	49.90	52.06	50.98
330	41.14	39.65	40.40	56.70	52.76	54.73
345	41.06	39.62	40.34	57.36	48.55	52.95
360	41.02	39.60	40.31	53.28	49.18	51.23
375	40.96	39.58	40.27	53.42	58.14	55.78
390	40.92	39.52	40.22	54.85	57.53	56.19
405	40.82	39.49	40.15	58.71	52.27	55.49
420	40.80	39.46	40.13	54.01	57.28	55.65
435	40.76	39.43	40.09	56.39	50.12	53.25
450	40.72	39.41	40.06	48.08	54.56	51.32
465	40.70	39.39	40.04	67.74	53.45	60.60
480	40.62	39.35	39.98	56.25	58.75	57.50

Table D-10 FO run under the MIX concentration (Mix=0.5 CMC)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Mix concentration	0.5 CMC	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	32.42	33.43	32.92	157.30	159.38	158.34
30	32.36	33.39	32.87	157.25	153.77	155.51
45	32.30	33.35	32.82	124.51	174.18	149.34
60	32.26	33.29	32.78	138.37	167.69	153.03
75	32.22	33.25	32.74	169.09	152.82	160.96
90	32.16	33.21	32.69	154.37	154.86	154.62
105	32.12	33.15	32.64	150.73	159.75	155.24
120	32.04	33.09	32.57	150.41	164.65	157.53
135	32.00	33.03	32.52	144.34	146.06	145.20
150	31.96	32.97	32.47	160.71	149.73	155.22
165	31.92	32.95	32.44	154.41	136.84	145.62
180	31.88	32.91	32.40	156.42	143.07	149.74
195	31.82	32.83	32.33	158.33	128.84	143.59
210	31.80	32.75	32.28	146.55	128.25	137.40
225	31.76	32.69	32.23	145.72	122.28	134.00
240	31.72	32.67	32.20	144.82	137.25	141.03
255	31.68	32.60	32.14	128.10	125.90	127.00
270	31.60	32.56	32.08	127.44	137.81	132.62
285	31.54	32.52	32.03	131.84	141.65	136.74

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	31.48	32.42	31.95	125.81	140.37	133.09
315	31.42	32.38	31.90	127.46	133.93	130.69
330	31.40	32.32	31.86	123.74	115.27	119.50
345	31.34	32.24	31.79	131.06	114.21	122.64
360	31.28	32.20	31.74	143.07	112.99	128.03
375	31.20	32.16	31.68	128.71	122.14	125.43
390	31.16	32.14	31.65	131.95	117.53	124.74
405	31.12	32.12	31.62	135.80	115.92	125.86
420	31.04	32.08	31.56	139.54	126.08	132.81
435	31.00	32.04	31.52	125.94	138.39	132.17
450	30.96	31.98	31.47	142.46	133.78	138.12
465	30.92	31.96	31.44	134.31	158.66	146.48
480	30.84	31.92	31.38	146.42	127.44	136.93

Table D-11 FO run under the combination concentration (Mix=1.0 CMC)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
MIX concentration	1.185	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, ^{o}C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	37.89	39.99	38.94	126.11	120.04	123.07
30	37.88	39.96	38.92	101.81	115.42	108.62
45	37.86	39.90	38.88	101.44	110.77	106.10
60	37.82	39.86	38.84	122.45	103.19	112.82
75	37.80	39.78	38.79	108.65	110.55	109.60
90	37.76	39.72	38.74	104.37	102.11	103.24
105	37.70	39.70	38.70	121.53	111.65	116.59
120	37.64	39.64	38.64	124.04	116.85	120.44
135	37.58	39.58	38.58	127.24	120.37	123.81
150	37.56	39.54	38.55	102.13	120.35	111.24
165	37.50	39.50	38.50	115.83	107.58	111.71
180	37.46	39.42	38.44	121.09	107.39	114.24
195	37.40	39.36	38.38	115.06	121.47	118.27
210	37.34	39.31	38.32	115.45	103.41	109.43
225	37.28	39.27	38.27	100.80	99.47	100.14
240	37.20	39.21	38.20	99.35	117.20	108.27
255	37.14	39.13	38.13	104.78	108.52	106.65
270	37.08	39.11	38.09	118.94	107.30	113.12
285	37.00	39.05	38.02	112.91	98.76	105.83

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	36.96	39.01	37.98	108.21	112.44	110.32
315	36.94	38.97	37.95	109.69	105.86	107.77
330	36.90	38.91	37.90	106.36	114.36	110.36
345	36.82	38.87	37.84	109.95	101.77	105.86
360	36.80	38.79	37.79	117.73	98.69	108.21
375	36.78	38.71	37.74	102.10	99.97	101.03
390	36.74	38.67	37.70	103.81	112.57	108.19
405	36.70	38.65	37.68	101.84	107.04	104.44
420	36.68	38.61	37.65	114.60	117.76	116.18
435	36.62	38.55	37.59	99.15	109.20	104.18
450	36.56	38.51	37.54	109.48	105.19	107.34
465	36.54	38.49	37.52	108.61	104.07	106.34
480	36.50	38.45	37.48	101.26	100.79	101.02

Table D-12 FO run under concentration (combination = 2.0 CMC)

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
MIX concentration	2.0 CMC	0.00
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	253.0(7.03)	253.0(7.03)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
0	0.00	0.00	0.00			
15	42.30	42.50	42.40	98.08	85.22	91.65
30	42.26	42.44	42.35	71.66	88.28	79.97
45	42.20	42.36	42.28	81.35	90.28	85.82
60	42.16	42.30	42.23	90.36	63.37	76.86
75	42.12	42.28	42.20	78.14	76.40	77.27
90	42.08	42.24	42.16	77.05	63.97	70.51
105	42.02	42.20	42.11	78.57	79.75	79.16
120	41.96	42.14	42.05	81.89	62.86	72.38
135	41.94	42.08	42.01	89.51	67.89	78.70
150	41.88	42.06	41.97	81.17	66.64	73.90
165	41.82	42.02	41.92	67.27	73.94	70.61
180	41.76	41.99	41.87	98.70	74.02	86.36
195	41.72	41.97	41.84	85.12	69.81	77.46
210	41.66	41.91	41.78	94.46	71.78	83.12
225	41.58	41.89	41.73	88.69	59.81	74.25
240	41.54	41.81	41.67	85.04	60.52	72.78
255	41.48	41.75	41.61	88.42	68.72	78.57
270	41.42	41.69	41.55	83.96	65.03	74.49
285	41.38	41.65	41.51	86.47	62.04	74.25

Time	J_w (L/m^2-h)			J_s (mmole/m^2/h)		
	Test-1	Test-2	Average	Test-1	Test-2	Average
300	41.32	41.61	41.46	89.18	63.97	76.58
315	41.22	41.53	41.37	86.42	75.20	80.81
330	41.16	41.45	41.30	84.45	71.51	77.98
345	41.12	41.41	41.26	82.81	66.47	74.64
360	41.06	41.31	41.19	76.84	71.08	73.96
375	41.02	41.29	41.16	81.96	72.19	77.07
390	40.98	41.21	41.10	84.10	62.28	73.19
405	40.94	41.17	41.06	91.95	69.73	80.84
420	40.88	41.11	41.00	90.75	62.27	76.51
435	40.82	41.05	40.94	89.98	69.74	79.86
450	40.78	40.99	40.89	81.90	75.43	78.66
465	40.76	40.91	40.84	87.83	73.75	80.79
480	40.72	40.89	40.81	81.99	79.69	80.84

APPENDIX E

Effect of foulant on feed solution containing mixture surfactant

Table E-1 FO process run under different mix solution

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
Mix concentration	1.0 CMC	0.00
Mix + humic acid	1.0CMC+100 mg/l HA	
Mix + colloids	1.0CMC+10^7 colloids	
Mix + humic acid	1.0CMC+10 mg/l boron	
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	17.0(0.48)	17.0(0.48)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)				J_s (mmole/m^2/h)			
	Mix	Mix+HA	Mix+CML	Mix+B	Mix	Mix+HA	Mix+CML	Mix+B
0								
15	37.90	36.76	37.34	36.84	126.59	98.19	189.58	130.79
30	37.88	36.78	37.20	36.78	122.53	106.51	192.17	127.71
45	37.86	36.74	37.10	36.76	122.36	108.54	199.59	110.61
60	37.82	36.68	37.04	36.73	133.53	103.28	175.94	121.16
75	37.80	36.68	36.97	36.68	121.86	106.57	170.78	119.48
90	37.76	36.70	36.87	36.66	135.74	112.49	173.98	128.62
105	37.70	36.72	36.81	36.62	123.00	111.47	176.13	129.67
120	37.64	36.68	36.75	36.55	125.59	110.39	164.40	111.64
135	37.58	36.67	36.67	36.50	128.95	109.25	175.69	115.05
150	37.56	36.72	36.57	36.43	114.00	107.85	165.98	125.69
165	37.50	36.74	36.53	36.38	117.83	86.96	163.48	115.57
180	37.46	36.68	36.46	36.34	113.23	109.44	174.64	115.82
195	37.40	36.67	36.40	36.28	137.31	92.13	165.81	118.06
210	37.34	36.68	36.36	36.22	127.79	97.66	167.74	125.11

225	37.28	36.70	36.23	36.18		123.30	98.74	163.67	120.81
240	37.20	36.67	36.15	36.11		131.95	109.78	163.90	134.20
255	37.14	36.65	36.11	36.02		117.35	90.30	174.79	137.26
270	37.08	36.65	36.07	35.96		121.56	97.13	177.75	136.69
285	37.00	36.63	36.02	35.92		135.52	94.17	202.23	129.80
300	36.96	36.68	35.91	35.83		111.05	90.70	183.48	123.51
315	36.94	36.72	35.77	35.68		122.94	99.12	183.46	127.22
330	36.90	36.67	35.75	35.58		129.69	97.56	188.05	116.41
345	36.82	36.70	35.73	35.54		123.22	96.40	190.99	137.40
360	36.80	36.72	35.65	35.52		121.39	91.00	212.61	136.74
375	36.78	36.67	35.54	35.43		126.05	101.37	198.42	133.94
390	36.74	36.68	35.53	35.36		127.90	94.17	178.50	136.67
405	36.70	36.65	35.41	35.32		126.20	92.68	195.77	124.63
420	36.68	36.70	35.34	35.26		129.35	95.52	196.52	123.10
435	36.62	36.72	35.24	35.24		134.05	101.38	211.34	123.40
450	36.56	36.68	35.15	35.22		134.62	109.72	192.49	133.03
465	36.54	36.68	35.03	35.18		134.34	92.51	208.63	139.84
480	36.50	36.70	34.96	35.16		137.15	90.77	214.81	137.56

APPENDIX F

Effect of cleaning agent on feed solution containing mixture surfactants

Table F-1 FO process run under different cleaning agents

Condition		
Solution/Side	Feed Solution (active layer)	Draw Solution (supporting layer)
DI-water	DI-water	0.00
0.1 M Nacl	0.1 M Nacl	
pH 11	pH 11	
Concentration (NaCl, M)	0.01	1.0
Osmotic pressure (π, atm)	0.48	48.9
Flow rate, ml/min (cm/s)	17.0(0.48)	17.0(0.48)
pH of solution	7.0	7.0
Temperature, °C	25	25

Time	J_w (L/m^2-h)				J_s (mmole/m^2-h)		
	DI	0.1M	pH11		DI	0.1M	pH11
0							
15	28.84	29.06	28.35		1240.99	825.47	503.85
30	28.80	28.98	28.19		1071.50	838.56	509.29
45	28.74	28.84	28.07		1024.42	811.60	469.38
60	28.65	28.78	27.99		1022.54	742.85	443.77
75	28.51	28.67	27.93		1114.40	779.93	458.87
90	28.39	28.59	27.83		1128.25	693.91	448.93
105	28.27	28.49	27.73		991.39	688.06	439.36
120	28.15	28.39	27.69		1040.67	712.15	417.47
135	28.05	28.25	27.65		1077.07	689.87	411.35
150	27.99	28.19	27.59		922.96	709.00	371.32
165	27.87	28.09	27.51		912.49	717.28	359.23
180	27.77	27.93	27.45		904.62	691.79	392.37
195	27.67	27.79	27.39		893.90	705.15	377.36
210	27.59	27.71	27.33		929.50	696.88	346.91
225	27.51	27.63	27.26		863.48	656.30	358.05
240	27.43	27.55	27.16		825.62	672.07	331.08

Time	J_w (L/m^2-h)				J_s (mmole/m^2-h)		
	DI	0.1M	pH11		DI	0.1M	pH11
255	27.35	27.43	27.04		1045.07	664.24	348.69
270	27.24	27.32	26.88		757.97	593.72	343.05
285	27.16	27.20	26.82		800.71	615.05	333.81
300	27.02	27.10	26.76		858.45	608.34	327.23
AV	**27.95**	**28.10**	**27.53**		**971.30**	**705.61**	**399.57**
STD	0.58	0.62	0.46		124.26	67.59	58.59
330	**30.35**	**21.34**	**31.94**		776.46	1081.51	119.64
345	**30.82**	**21.24**	**31.46**		673.34	1268.18	118.83
360	**30.24**	**21.12**	**31.82**		613.32	927.49	117.96
375	**30.76**	**21.04**	**32.01**		734.39	951.03	117.10
390	**30.00**	**20.98**	**31.71**		633.65	919.89	116.20
405	**29.96**	**20.92**	**31.36**		594.47	1062.82	115.30
420	**30.05**	**20.86**	**31.56**		638.58	1118.16	114.37
435	**29.98**	**20.80**	**32.00**		674.12	1101.46	113.42
450	**30.07**	**20.74**	**31.98**		605.35	1176.24	112.46
465	**30.21**	**20.68**	**32.26**		545.12	839.09	111.51
480	**30.15**	**20.61**	**32.14**		556.86	1153.59	110.56

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