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FORWARD OSMOSIS AS A REVERSE OSMOSIS PRE- TREATMENT IN TREATING BRACKISH WATER AND WASTEWATER

A Thesis in
Environmental Pollution Control
by

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ABSTRACT

As an increase in water demand and the lack of resources, many communities are using seawater and brackish water as their principal water source. Through years, water desalination has become more common in the water treatment field using reverse osmosis as the main technique to provide clean water to customers. However, this methodology is energy-intensive. Membrane fouling and brine disposal are also aspects of concern. In this study we evaluated the feasibility of implementing forward osmosis as a pre-treatment for the reverse osmosis desalination process. Highly salt-concentrated brackish water (retentate) from the reverse osmosis process was used as the draw solution. Secondary treatment wastewater was used as the feed solution in order to dilute the concentrated brackish water.

Lab scale experimental results showed that the average water flux of the Forward Osmosis membrane was $2.0 \text{ L/m}^2\text{-hr}$. After 50 % dilution of total dissolved solids (TDS) on the draw solution, the membrane flux was still stable above $1 \text{ L/m}^2\text{-hr}$. During 23 hours operation there was no observed flux decline due to membrane fouling. Experiments confirmed that the membrane flux is directly proportional to the temperature. As the temperature of the water was increase from 10°C to 60°C , an increment in the water flux from $1 \text{ L/m}^2\text{-hr}$ to $3 \text{ L/m}^2\text{-hr}$ was observed. Compared to temperature, pH has little effect on the membrane flux. There was no observed flux decline due to high turbidity.

Besides stable flux and low fouling rate, the Forward Osmosis membrane used in this study also showed high pollutants rejection ratio which might transferred from the feed solution (secondary treated wastewater) to the draw solution (concentrated brackish water) through the FO membrane. It was determined that the Spectral Absorption Coefficient, using UV_{254}

wavelength, of the draw solution increased slightly from 0.195 to 0.211 after 8 hr running, indicating that the FO membrane provided a good organic matter rejection. The Forward Osmosis membrane also proved having a good rejection of disinfection byproducts (DBPs). Based on this study, forward osmosis combined with reverse osmosis is a potential technology for wastewater and concentrate brackish water reuse.

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Chapter 1

Introduction and Study Approach

1.1 Water Resource and Water Shortage

Water is an essential human need and over the next decade the number of people affected by severe water shortages is expected to increase fourfold. In the developing countries that are most affected, 80-90% of all diseases and 30% of all deaths result from poor drinking water quality [15]. There is growing recognition by governments and corporations that the future prosperity is intimately tied to the availability of fresh and safe water. Studies proved that wastewater, brackish water, and seawater have great potential to fill the coming requirements but the cost of energy and the investment in equipment required for purification and or desalination limited the ability to exploit these resources in many parts of the world.

1.1.1 The Application of Unconventional Water Resources for Drinking Purpose

1.1.2 Secondary Treated Wastewater

Increments in population and climate changes are causing many communities to face water supply challenges. The idea or possibility of reuse wastewater instead of discharging is increasing the attention. Over the last ten years the safe use of impaired waters it's been studied. Strategies in how to minimize the health and environmental risk are in a development process

with the innovation of technologies and risk assessment processes [37]. The reuse of wastewater for other applications rather than drinking purpose is already established like for example irrigation of golf courses or industrial cooling [38]. Wastewater contains a wide range of pollutants which could affect human health. The presence of some compounds in reclaimed water may be of concern in drinking water, but not in water intended for landscape irrigation [38]. It is very important to understand and estimate the risks of reusing wastewater. Quality assurance is very important in every process using impaired water. Existing regulations does not include specific requirements for the municipal wastewater effluent like maximum total dissolved solids (TDS) that is discharge in the water bodies. The parameters regulated by the Environmental Protection Agency (EPA) are summarized in table 1-1. Adjustments to regulations and acts should be considered; wastewater is becoming an important source of water.

Table 1-1. EPA Secondary Treatment Standards

Parameter	30-Day Average	7-Day Average
5-Day BOD	30 mg/l	45 mg/l
TSS	30 mg/l	45 mg/l
pH	6 – 9 s.u. (instantaneous)	-
Removal	85% BODs, and TSS	-

Source: http://www.epa.gov/npdes/pubs/chapt_05.pdf

1.1.3 Sea Water and Brackish Water

As an increase in water demand and the lack of resources, many utilities are using seawater and brackish water as their principal water source. Through years, water desalination has become more common in the water treatment field as the main technique to provide safe water to

customers. Now day, the most used technology for water purification and desalination is reverse osmosis. RO uses hydraulic pressure to oppose, and exceed, the osmotic pressure of an aqueous feed solution to produce purified water. The applied pressure is the driving force for mass transport through the membrane. In literature there are numerous publications on the use of RO for water treatment using sea water and brackish water as the feed solution. The advantage of RO is that the water permeating the membrane is in most cases fresh water ready for use.

1.2 Problems existing in brackish water reuse process and technologies

Most of the physical processes used in desalination, in order to obtain high recovery, required high energy consumption which implies high capital and operational costs. The cost of desalination process including infrastructure, maintenance and energy are very high compared to the cost of other common alternatives like to treat surface water and/or ground water. The high energy requirements of this process pose a major challenge. Theoretically, about 0.86 kWh of energy is needed to desalinate 1 m³ of salt water (34 500 ppm). This is equivalent to 3 kJ kg⁻¹. The present day desalination plants use 5 to 26 times as much as this theoretical minimum depending on the type of process used. Clearly, it is necessary to make desalination processes as energy-efficient as possible through improvements in technology and economies of scale [36].

Environmental considerations are important on desalination process. All desalination processes produced large amounts of brine which may represent a potential factor for biofouling, and scale deposits on membrane causing sensitivity to fouling and service life issues. Disposal of concentrated brine into the water bodies also represents a big issue when using RO desalination technology. Due to environmental impacts of high salinity water, the discharge of desalination

concentrates is prohibited in many parts of the world which limited the ability to exploit these resources. Over the last years strict regulations have been establish in order to protect water bodies, aquatic life, and public drinking water sources by limiting the amount of total dissolved solids that could be discharge into waterways.

1.4 Research Target

In this study we evaluated the feasibility of forward osmosis in treating the highly salt-concentrated brackish water from reverse osmosis process. By implementing forward osmosis, the concentrated stream can be diluted using treated wastewater. The diluted brackish water can be reuse in the reverse osmosis process helping reduce the energy consumption. A substantial decrease in the discharge concentrated brackish water volume can be achieved.

Study Objectives

The objective of this work is to investigate the FO membrane flux variation law under different water quality conditions, membrane fouling process with operation time, the membrane rejection effects on DBPs pollutants, and explore the technical feasibility of Forward Osmosis in diluting brackish water concentrate using wastewater as a potential water source.

Chapter 2

Background-Literature Review

2.1 Forward Osmosis

Forward osmosis is the physical process that occurs when two different solutions contact opposite sides of a semi-permeable membrane. A net movement of water occurs across the membrane driven by a difference in osmotic pressure. A selectively permeable membrane allows passage of water, but rejects solute molecules and ions as shown in Figure 2-1. Water molecules will therefore move from one solution to another to achieve maximum mixing [3].

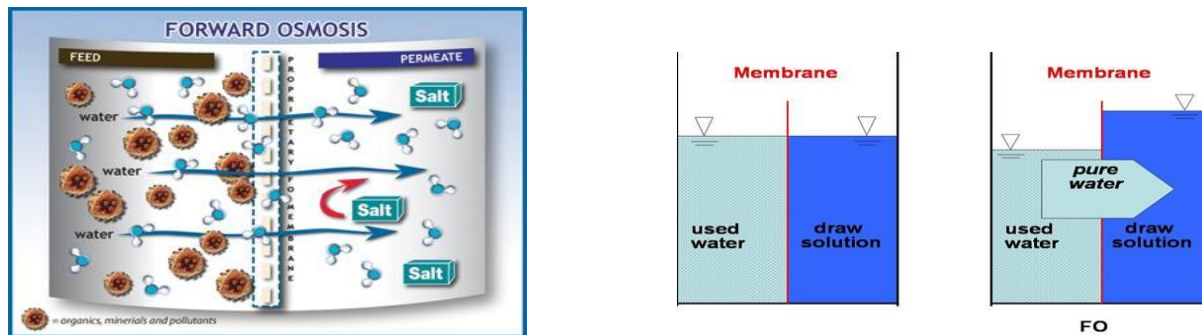


Figure 2-1. Illustration of Forward Osmosis Process

Source: Hydration Technology Innovations (http://www.htiwater.com/technology/forward_osmosis/)

The strength of this mixing tendency is measured by the solution's osmotic potential or osmotic pressure. The osmotic potential is high for concentrated solutions and low for diluted

solutions. It is also roughly proportional to the molar concentration of dissolved species. Water always moves from the solution with lower osmotic potential to the solution with higher osmotic potential as shown in Figure 2-2. It's important to mention that the greater the difference in osmotic potential, the faster water moves through the membrane. Osmotic pressure is the pressure which, if applied to the more concentrated solutions, would prevent transport of water across the membrane. In the ideal case, the osmotic pressure is directly proportional to the concentration of the solute. Forward osmosis uses osmotic pressure differential across the membrane as the driving force for transport of water through the membrane, rather than hydraulic pressure differential as in reverse osmosis. The FO process results in the concentration of a feed stream and the dilution of a highly concentrated stream referred to as the draw solution [1].

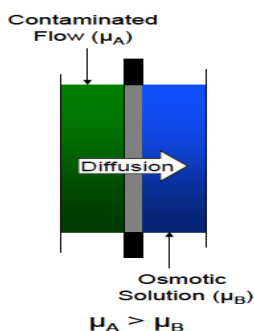


Figure 2-2. Illustration of Osmotic Potential Difference

Source: J.E. Miller, L.R. Evans, Forward Osmosis: A new Approach to Water Purification and Desalination, Sandia National Laboratories, Albuquerque, NM, 2006.

The concentrated solution on the permeate side of the membrane is the source of the driving force in the forward osmosis process. It is also known as draw solution, osmotic agent, driving solution, or brine. When selecting a draw solution, the main criterion is that it has a higher osmotic pressure than the feed solution. They also should ideally be inert, stable, of

neutral or near neutral pH, and non-toxic. They should not degrade the membrane chemically (through reaction, dissolution, or adsorption) or physically (fouling) and should have minimal effects on the environment or human health [1, 2, 3]. It should also be inexpensive and very soluble. For specific applications, additional criteria will apply. In forward osmosis selecting the draw solution determines the end use of the FO product [6]. In some applications is very important to select a suitable process to reconcentrate the draw solution after it has been diluted in the FO process [1]. If the final desired product is fresh water, the draw solution needs to be easy and completely recoverable from water.

The advantage of using forward osmosis compared to pressure-driven membrane processes like reverse osmosis is that it operates at low or no hydraulic pressure, translating into less energy used. It has the potential to significantly reduce both capital and energy costs. In forward osmosis, natural osmotic pressure in the draw solution pulls water through the membrane, leaving solids and foulants behind in the concentrated feed solution. Because of this it is anticipated that many of the fouling issues and service life issues associated with reverse osmosis membranes should be avoided. It also has high rejection of a wide range of contaminants [3].

2.2 FO Membranes

Usually, any dense, non-porous, selectively permeable material can be used as a membrane in FO process. Membranes need to provide high water permeability, high rejection of solutes, high chemical stability, and high chemical strength. The desired characteristics of membrane for FO would be high density of the active layer for high solute rejection; a thin membrane with minimum porosity of the support layer for low internal CP, and therefore, higher

water flux; hydrophilicity for enhanced flux and reduce membrane fouling; and high mechanical strength [1].

During 1990's a special membrane for FO was developed by Osmotek Inc. currently HTI (Hydration Technologies Inc.). This membrane is made of cellulose triacetate (CTA). The CTA membrane lacks a thick support layer. Instead, the embedded polyester mesh provides mechanical support. A picture of the membrane is shown in Figure 2-3. This membrane has been tested in a wide variety of applications by different research groups. It is also used successfully in commercial applications of water purifications for military, emergency relief, and recreational purposes. Based on studies performed by the manufacture company, the rejection rate is around 85-95 %. It can stand temperatures around 45°C and a pH range of 2 to 12.

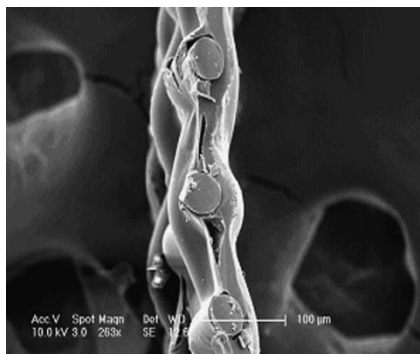


Figure 2-3. Forward Osmosis CTA membrane

Source: J.R. McCutcheon, R.L. McGinnis, M. Elimelech, A novel ammonia-carbon dioxide forward osmosis desalination process, *Desalination* 174 (2005) 1-11.

2.2.1 Membrane Physical Cleaning

The membrane life of the membrane is a function of the feed solution source, frequency of cleaning, system design, and the operating conditions. Results from previous investigations illustrated that water flux decline due to membrane fouling was partially reversible with physical cleaning of the FO membrane, and that moderate chemical cleaning was able to fully recover water flux [23]. Figure 2-4 shows the membrane flux restoration after cleaning the CTA membrane.

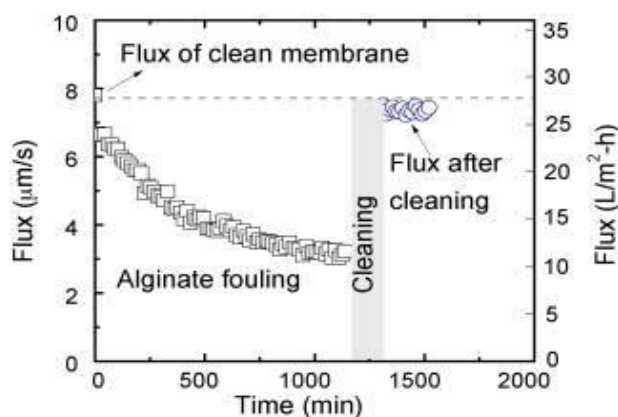


Figure 2-4: Membrane flux restoration after cleaning. Experimental conditions for fouling experiments: draw solution containing 4 M NaCl; feed solution containing 200 mg/L alginate, 50 mM NaCl, and 0.5 mM Ca^{2+} ; crossflow velocity of 8.5 cm/s; pH of 5.8; and temperature of 20 ± 1 °C. Cellulose acetate (CA) membrane from Hydration Technologies, Inc. was used.

Source: B. Mia, M. Elimenech, Organic fouling of forward osmosis membranes: Fouling reversibility and cleaning without chemical reagents, *Journal of Membrane Science* 248 (2010) 337-345.

In order to breaking up the fouling layer that can be formed on the membrane because of the deposition of solids from the feed solution, osmotic backwashing can be used. This technique is achieved by replacing the feed solution with deionized water. Modified backwashing can also

be used and in this process the draw solution is replaced by deionized water. In both processes the water permeation removes the cake layer formed on the membrane restoring the water flux.

2.3 Forward Osmosis Applications

Forward osmosis has been studied through the years for a range of applications but few publications appear in literature. New ones are emerging in separation processes for wastewater treatments, water purification, food processing, pharmaceutical industry and seawater/brackish water desalination [1]. FO has been used to treat industrial wastewater, to concentrate landfill leachate (at pilot-and full-scale), and for reclaiming wastewater for potable reuse in life support systems (at demonstration-scale). It has also been used for generation of electricity from saline and fresh water [9, 1, 2].

Now day, FO is emerging in the dewatering processes specifically in desalination applications. Commercial desalination technologies used to desalinate seawater and inland brackish waters, including electro-dialysis, reverse osmosis, multistage flash distillation, and vapor compression, can be cost-prohibited due to high capital and energy costs [2]. FO is an emerging process that might one day help solve this problem. The ability of FO to treat waters with high solid content or fouling potential is particularly attractive. Several patents have been awarded for different methods and systems for water desalination by forward osmosis but most of them have not matured or proven feasible.

Chapter 3

Methodology

3.1 James City County Williamsburg, VA Drinking Water System

James City County is a 144-square mile municipality located at the head end of the Virginia peninsula, between the James and York Rivers. JCDA operates the largest solely dependent groundwater based water system in the Commonwealth of Virginia. The majority of its groundwater supply system is derived from the Potomac and Chickahominy-Piney Point Aquifers. The JCSA's water system currently operates a Central Water System and six independent systems.

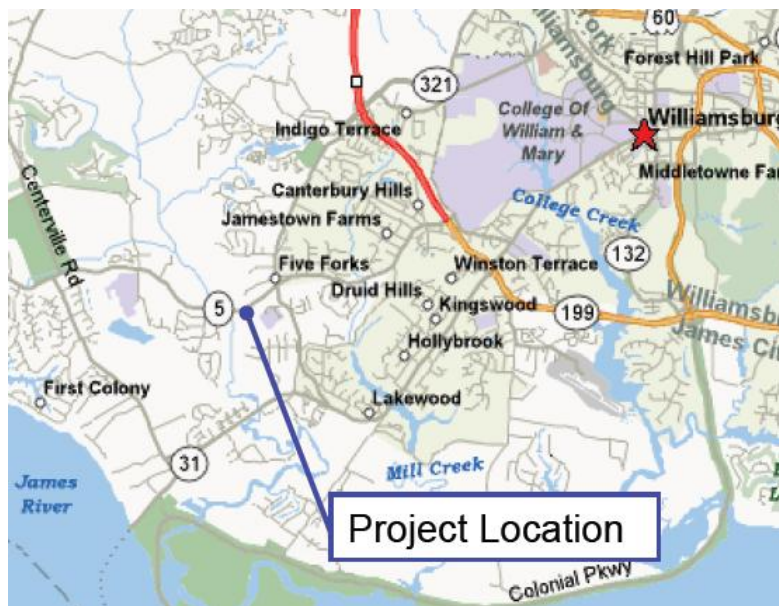


Figure 3-1. Map of James City Service Authority Five Forks Water Treatment Facility

Source: Google Maps

The Five Forks Water Treatment Facility consists of five on-site wells drawing brackish groundwater from the Middle and Lower Potomac Aquifers (Table 3-1). In order to obtain potable water, a reverse osmosis treatment process is used to extract salts and other minerals. This extraction, also known as concentrate or brine, is discharged into the James River. For every five (5) million gallons of potable water produced, approximately one million gallons of concentrate are discharged into the James River.

3.1.1 Existing RO Desalination Process in Jamestown, VA

Four (4) reverse osmosis treatment skids, shown in figure 3-4, are provided in the treatment facility for desalination of the raw water extracted from the Lower Potomac Wells. The RO skids consist of a two-stage membrane system. The first stage consists of 20 vessels and the second stage consists of 10 additional vessels. Vessels contain six (6) membranes each.

Raw water is pumped into the first stage membranes of the RO skid. The permeate is discharged to the permeate line. The concentrate from the first stage becomes the feed water for the second stage. The permeate from the second stage combines with the permeate from the first stage and is piped to the common RO skid total permeate line. The concentrate from the second stage is piped to the common concentrate line which is discharged into the James River. A process flow diagram is shown in figure 3-3.

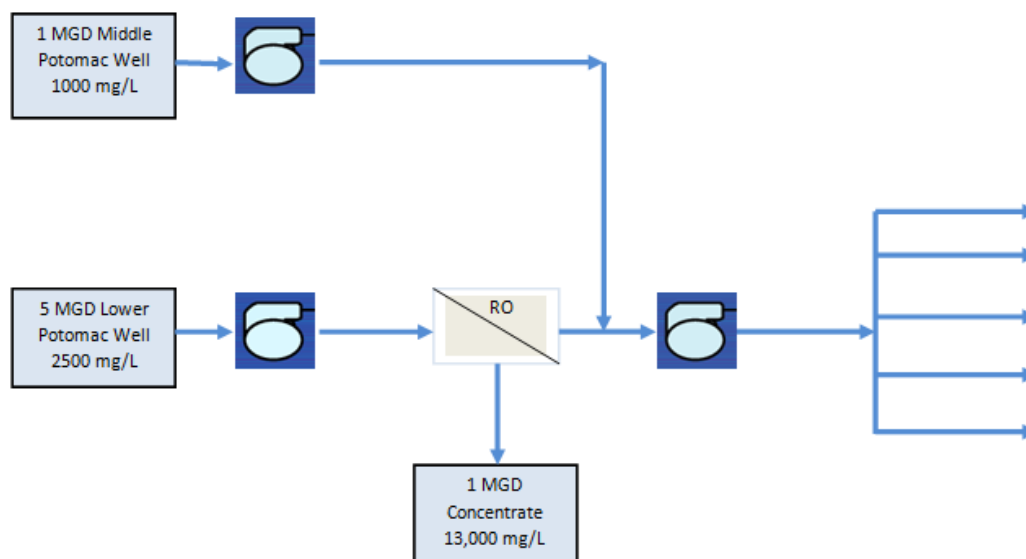


Figure 3-2. Existing James City Service Authority Reverse Osmosis Desalination Process

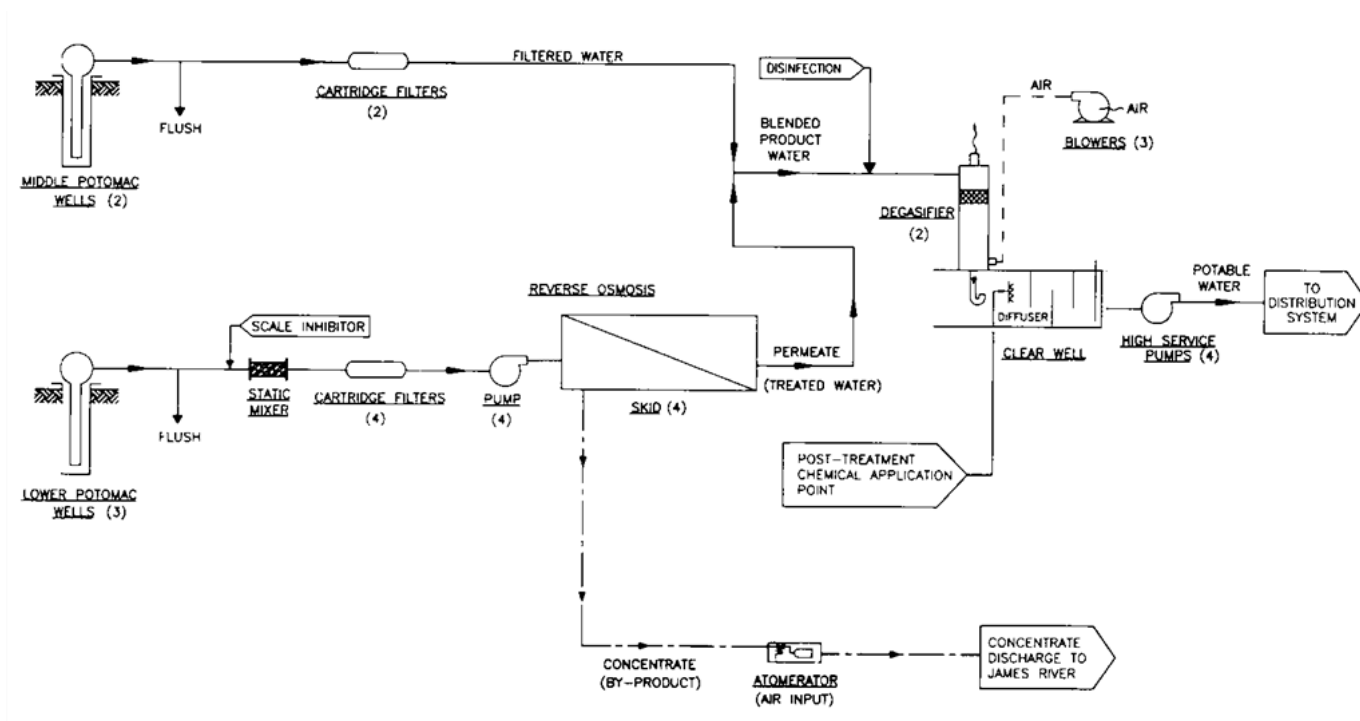


Figure 3-3. James City RO Desalination Process Flow Diagram

Source: James City Service Authority Williamsburg, VA



Figure3-4. Reverse Osmosis Skid

Source: James City Service Authority Williamsburg, VA

Table 3-1. James City Authority Brackish Water Quality

Parameters	Middle Potomac	Lower Potomac
Cond.	1500 umhos/cm	4500 umhos/cm
TDS	1000 ppm	2500 ppm
Alkalinity	320 ppm	340 ppm
Hardness	15 ppm	80 ppm
Na	417 ppm	1100 ppm
Cl	340 ppm	1250 ppm
SDI	2 +/-	< 1
Turb.	< 1 NTU	< 1 NTU
Fe	0.01 ppm	0.02 ppm
SiO₂	41 ppm	29 ppm
pH	7.9-8.2	7.6-7.8
Radon	150 pCi/L	200-300 pCi/L

3.2 Proposed Updated System-Implementation of Forward Osmosis in the existing Reverse Osmosis Desalination Process

The raw water used in Jamestown, VA drinking water plant is pumped from two different wells. One of them supplies approximately 1.0 MGD groundwater with low salt concentration (Middle Potomac Well). The other well supplies approximately 5.0 MGD groundwater with a higher salt concentration (Lower Potomac Well), a typical kind of brackish water. Brackish water composition of both wells is explained in table 3-1. After being treated with RO membranes, nearly all of the salt in the water is removed. In order to maintain the normal range of salt contents in the potable water going into the distribution system, the RO effluent water is blended with the groundwater pumped from the Middle Potomac Well which contains low salt concentration as shown in Figure 3-2 and 3-3.

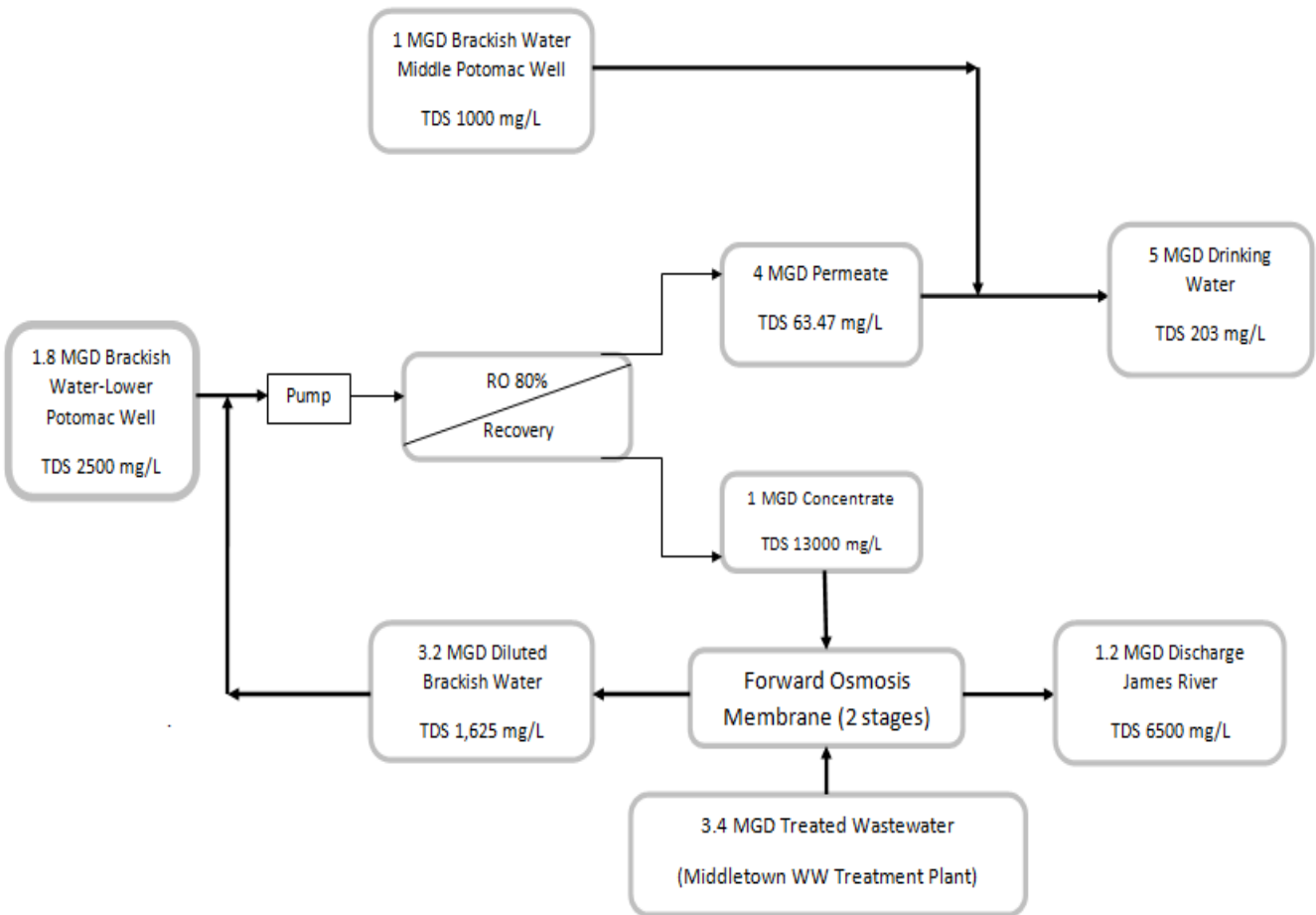


Figure 3-5. Diagram showing FO as a pre-treatment in the RO Desalination Process

The water recovery in the RO unit is around 80% (James City Authority Williamsburg, VA). Approximately 1.0 MGD of the concentrated brackish water is discharged from the system into the James River. The concentration of the total dissolved solids in the underground (Lower Potomac Well) brackish water is approximately 2500 mg/L, and increased to approximately 13000 mg/L during the RO treatment process, calling this stream concentrated brackish water. This brine is then discharged into the James River. To minimize the effects of the highly salt

concentrated brackish water into the environment, a FO system is being considered to be added to the existing RO process in order to dilute and reuse the concentrated brackish water. In the updated system, a two stage FO membrane units were designed. A process diagram is provided in figure 3-5. Applying the dilution effects of the FO process, the concentrated brackish water will be diluted using impaired water. In this case wastewater will be used as the water source for the process. By diluting the draw solution its osmotic pressure declines being lower the hydraulic pressure required during the RO process.

The updated system consists of a two stage FO process. The two-stage process diagram is shown in figure 3-6. In the first stage the concentrated brackish water (1 MDG) will be diluted one time using wastewater. Sixty (60 %) percent will be discharged into the James River and forty (40 %) percent will be treated in the FO second stage in which is diluted four (4) times having a final flow of 3.2 MGD of diluted brackish water with a concentration of 1625 mg/L which means that only 1.8 MGD of underground water will be needed. After the second stage, the diluted brackish water returns to the beginning of the RO process diluting the raw brackish water coming from the Lower Potomac Well to a concentration of 1940 mg/L reducing the salt concentration by a 22.4 %.

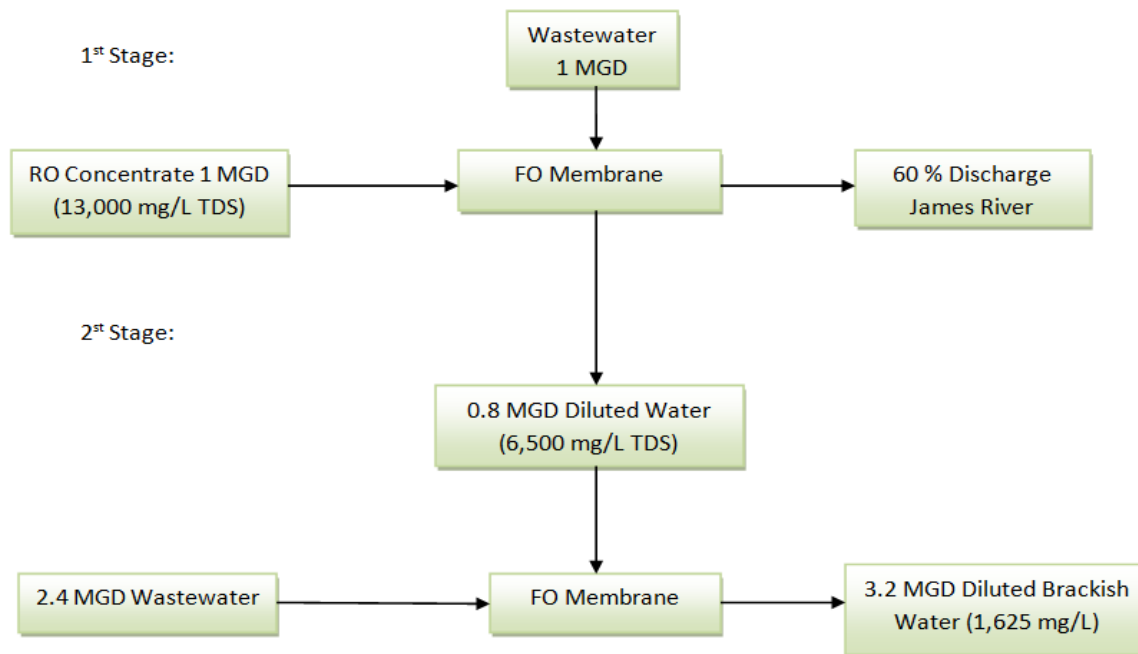


Figure 3-6. Forward Osmosis Two Stages Dilution Process

A reduction of almost 50% in the salinity of the discharge concentrate is possible to accomplish this way minimizing the environmental impact in the James River. The proposed two stages FO process notably reduces the salinity that it's been discharged. Mixing the FO diluted brackish water with the brackish water from the well before the RO declines its osmotic pressure reducing the hydraulic pressure require by RO during desalination. This allows a reduction in the energy consumption. The implementation of FO into the RO process allows the use of impaired water, in this case wastewater, which is an innovative and effective way of drinking water production using the same or less amount of the brackish water. This process is not only applicable to new plants but also to existing plants.

Actually, RO concentrate with 13000 mg/L TDS has been discharge into the Jamestown River with potential problems with fluoride (7 ppm). Implementing FO can help reduce TDS

concentration to almost 6500 mg/L which means a 50% reduction in the discharged concentration. In order to investigate the feasibility of the suggested brackish water purification process, laboratory scale experiments were designed and conducted using brackish water as draw solution and secondary treated wastewater as feed solution.

3.3 Materials and Methods

3.3.1 Feed Solution

Although the focus of the investigation was to use impaired water (wastewater) as the feed solution, some experiments were performed using deionized water (DI) in order to have a better understanding of the FO process and the effect of the feed solution on the membrane flux.

Wastewater Middletown, PA WWTP

Middletown owns and operates 2.2 million gallons per day municipal wastewater treatment plant that provides service for the Borough of Middletown and Royalton and portions of Lower Swatara Township. Existing wastewater treatment plant process units include a solids grinder and grit removal, primary clarification, biological treatment with clarification, chlorine addition for disinfection, and aeration prior to discharge into the Susquehanna River. Dechlorination if needed, is provided by the addition of sodium bisulfate. Phosphorous is removed by ferrous chloride addition. The biosolids stabilization process consists of aerobic digesters with coarse bubble diffusers. Liquid biosolids are dewatered by a belt filter press and pasteurized prior to land application. Dewatered biosolids and the pasteurized end product are

stored in covered areas at the wastewater plant site [22]. Composition of the Middletown Wastewater is summarized in table 3-2.

Table 3-2. Characteristics of wastewater effluent

Wastewater-Secondary Effluent	
pH	7.4-7.6
TSS, mg/L	5.0
Nitrate, mg/L NO₃-N	1.5-3.0
Ammonia, mg/L NH₃-N	0.1

3.3.2 Draw Solution

Experiments were conducted with various draw solution. A NaCl solution was used to study the effect of draw solution concentration on the membrane flux and also to investigate the reverse solute transport through the membrane. The focus of this investigation was to use concentrate brackish water as the draw solution. Synthetic brackish water with a composition summarized in table 3-3 was used to conduct experiments with the objective of investigating the effect of TDS concentration on the membrane flux. Further experiments were performed using the concentrate brackish water. This brine is the retentate from the reverse osmosis (RO) process in Jamestown, VA. The composition of the concentrate is summarized in table 3-4.

Table 3-3. James City Authority RO Brackish Water Concentrate Characteristics

TDS	13000 ppm
Na	5000 ppm
Cl	6000 ppm
SO₄	500 ppm
NO₃	3 ppm
F	7 ppm
NH₄	1.5 ppm
pH	8.3
DO	> 4 ppm

3.3.3 Experimental Setup and System Operation

A bench-scale FO system was designed for this study which included membrane permeation unit, water circuiting system, and monitor and data recording system. An image of the FO system is provided in Figure 3-7. The permeation cell was made of acrylic sheet as shown in figure 3-8. The membrane permeation unit was constructed with symmetric flow channels on both sides of the membrane. A 50 μm thick membrane coupon with an effective surface area of 0.0032 m^2 was put in the cell. The membrane was provided by Hydration Technologies, Inc. (Albany, OR) and it was designed with an embedded polyester mesh and a polymer porous support layer to give the membrane asymmetry and additional mechanical stability.

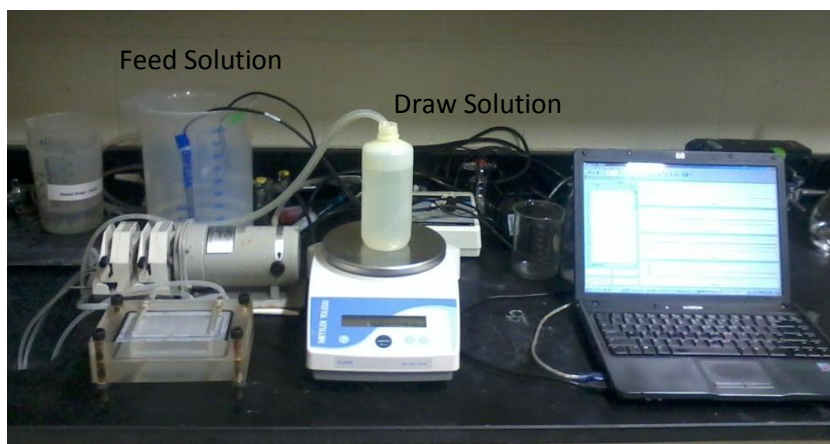


Figure 3-7. Forward Osmosis experimental setup

3.3.4 Determination of Water Quality

Operation parameters, such as solution temperature, pH, and conductivity were monitored on-line with corresponding sensors, and recorded using Logger Pro 3.8.6 software from Vernier Software & Technology.

3.3.5 Experimental Methods

Increase in draw solution volume was recorded using a digital balance (TL2100, Mettler Toledo, Germany) also shown in Figure 3-7. Absorbance in feed and draw solutions was measured using UV Spectrophotometer (Spectra Max M2, Molecular Devices, California, USA) shown in figure 3-9. Disinfection byproducts present in both feed and draw solution were measured using a Gas Chromatography (GC System 6890 Series, Hewlett Packard, USA).

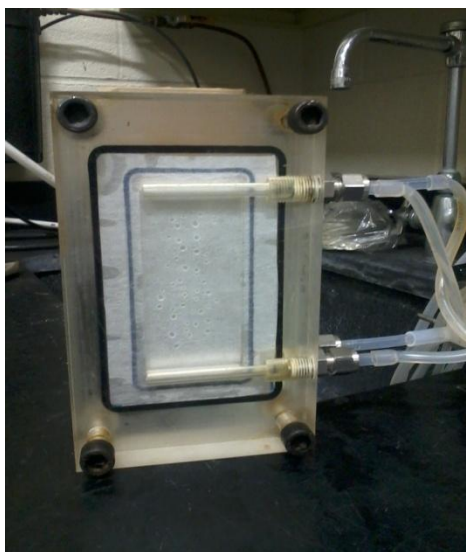


Figure 3-8. Acrylic permeation cell with CTA membrane



Figure 3-9. UV Spectrophotometer

Chapter 4

Experimental Results and Discussion

4.1 Forward Osmosis Membrane Flux

There are many factors that affect the water flux through the forward osmosis membrane.

Some of these factors are:

- The osmotic pressure difference across the active layer of the membrane. As the dilution of the draw solution occurs, the difference in osmotic pressure gets lower, decreasing the water flux through the membrane.
- Membrane fouling due to concentration polarization may decrease the membrane flux.
- Higher temperatures may increase the membrane flux.

The general equation describing water transport in forward osmosis is given by equation (1)

$$J_w = A (\sigma \Delta \pi - \Delta P) \quad (1)$$

where J_w is the water flux, A the water permeability constant of the membrane, σ the reflection coefficient, and ΔP is the applied pressure [1]. For FO, ΔP is zero making the water flux directly proportional to the difference in osmotic pressure. The flux direction of the permeability water in FO and RO are illustrated in figure 4-1.

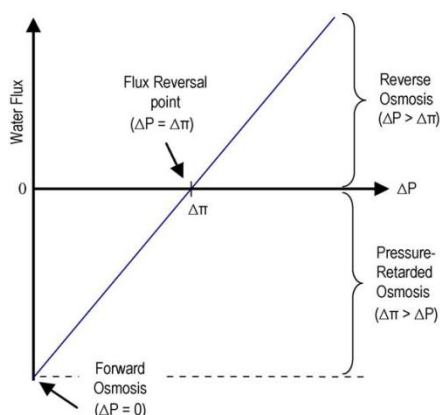


Figure 4-1. Direction and magnitude of water flux as a function of applied pressure

Source: T.Y. Cath, A.R. Childress, M. Elimenech, Forward Osmosis: Principles, applications, and recent developments, *Journal of Membrane Science* 281 (2006) 70-87.

4.1.1 Study of membrane flux under expected conditions

Experiments were designed to study the membrane flux and fouling potential of the process. Experiments were conducted using concentrated brackish water as the draw solution and wastewater as the feed solution.

After 20 hours of operation, it was found that the membrane flux decreased from 2 L/m²-hr to approximately 1.3 L/m²-hr. During the operation time, the flux never reached the value of 1 L/m²-hr which represent a good result for our investigation. The average membrane flux was 1.5 L/m²-hr. Results are shown in Figure 4-2. The flux decline may be due to the dilution of the draw solution. As dilution occurs the difference in osmotic pressure decreases causing a decline in the water flux. Proper selection of a suitable draw solution is very important.

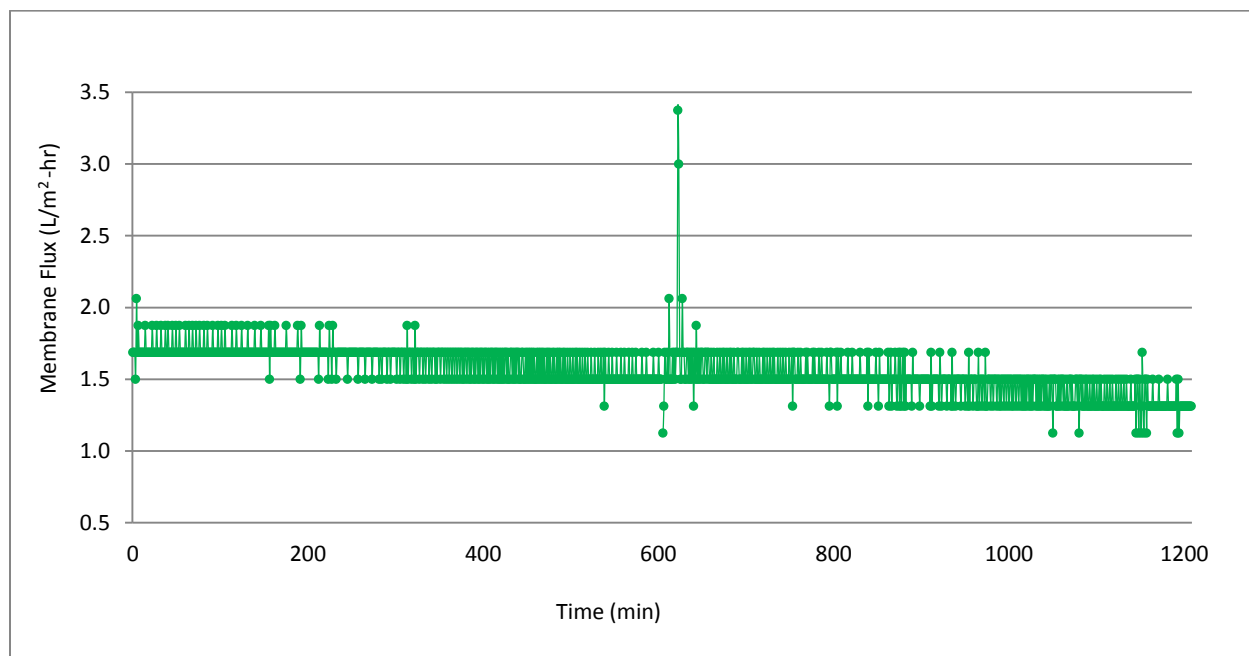


Figure 4-2. Membrane water flux during long time operation (20 hours)

The higher the concentration in the brackish water, the higher the water fluxes through the membrane. For the concentrated brackish water a flux between 1.5 and 2 $\text{L/m}^2\text{-hr}$ was obtained being this flux three times higher than the water flux obtained with the raw brackish water as shown illustrated in figure 4-3. This was also reflected in the dilution process of the draw solution. For the concentrated brackish water the volume increase was of about 18 mL and for the brackish water the volume increased just 3 mL. Results are shown in figure 4-4.

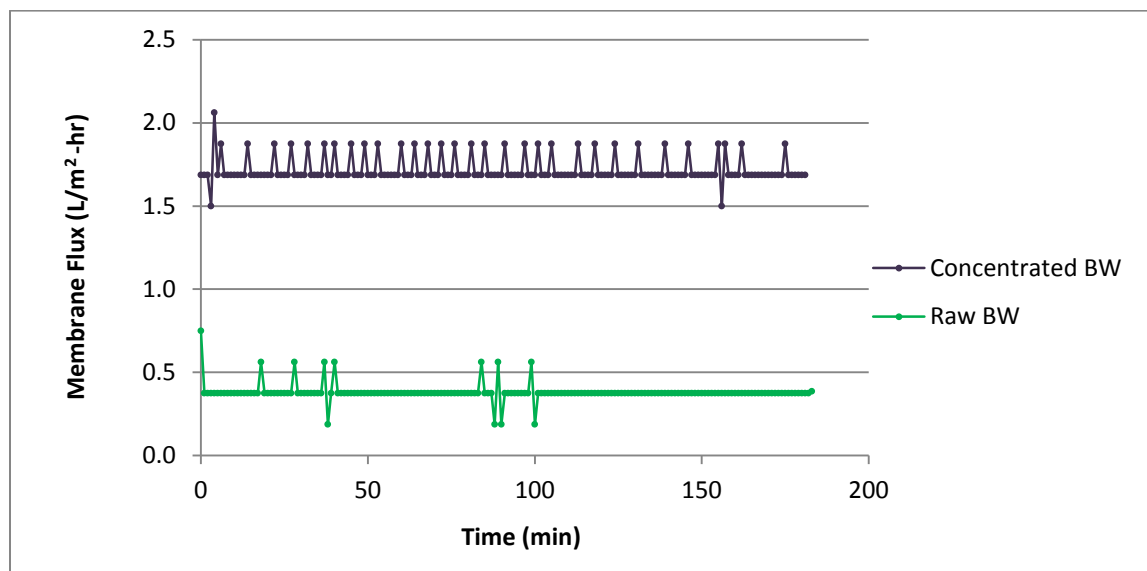


Figure 4-3. Comparison of membrane flux between raw brackish (Lower Potomac) water and concentrated brackish water (discharged into James River).

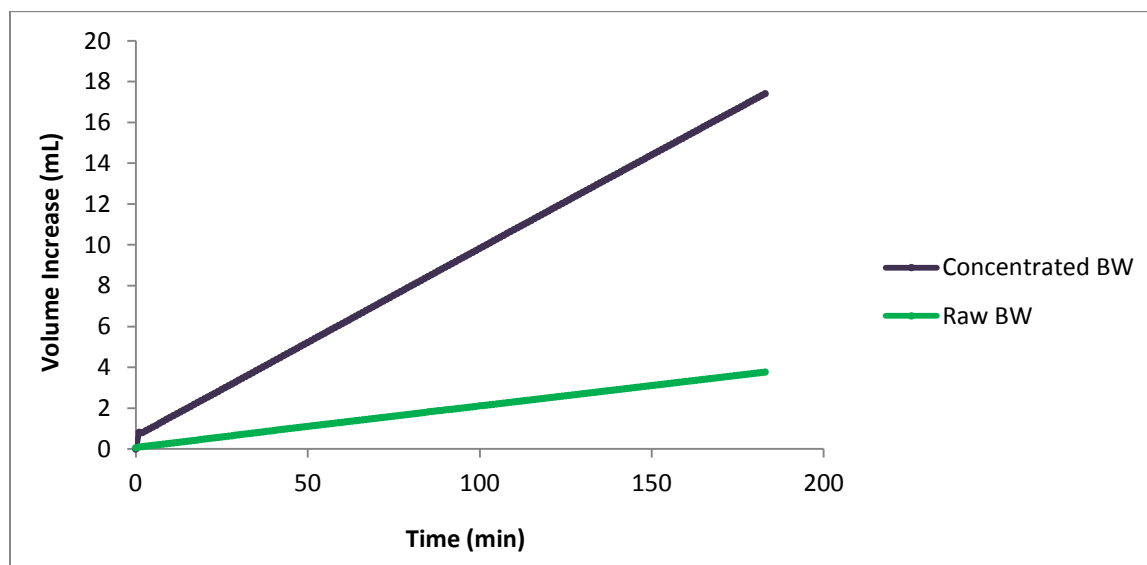


Figure 4-4. Comparison in volume increase between raw and concentrate brackish water

Brackish water has a very high concentration of TDS. This could turn into having fouling problems in the FO membrane decreasing the water flux. In order to observe the effect of the concentrate brackish water on the membrane flux and the fouling potential, synthetic brackish water was prepared in the laboratory. The composition of the synthetic water is summarized in table 4-1.

Table 4-1. Synthetic brackish water composition

Parameter	Concentration (mg/L)
NaCl	9459
KCl	210
MgCl ₂	212
CaCl ₂	386
NaSO ₄	740
NaHCO ₃	2892
Na ₂ SiO ₃	240

During the experiment, wastewater was used as the feed solution. The system ran for 6.5 hours. An increase in volume of approximately 34 mL in the draw solution was observed. Results are shown in figure 4-5. Meanwhile, the membrane flux was stable throughout the running time in a range of 1 to 2 L/m²-hr as observed in figure 4-6.

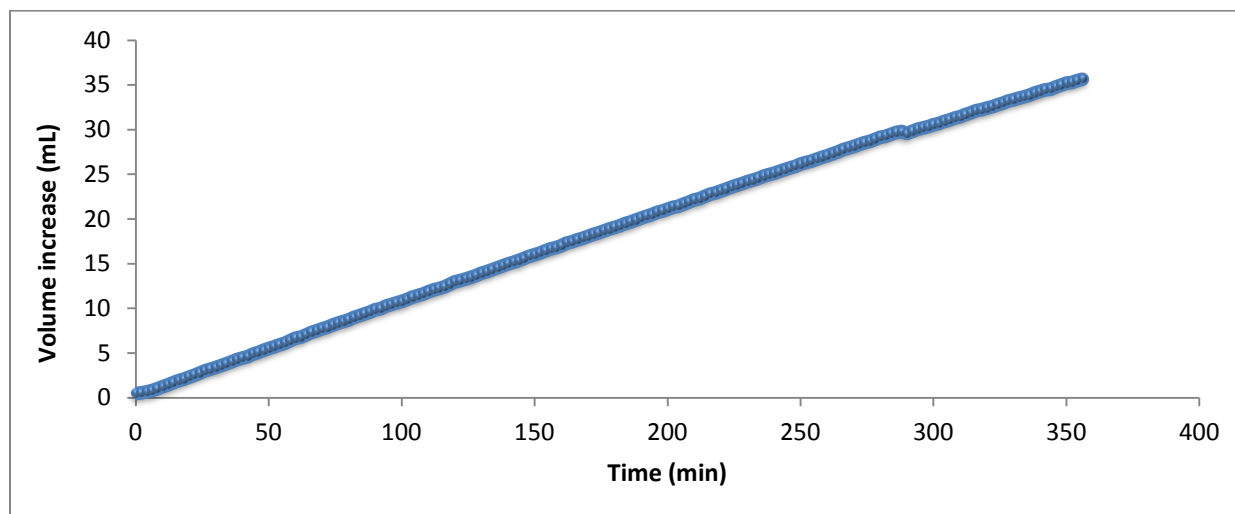


Figure 4-5. Increment in brackish water volume as a function of time

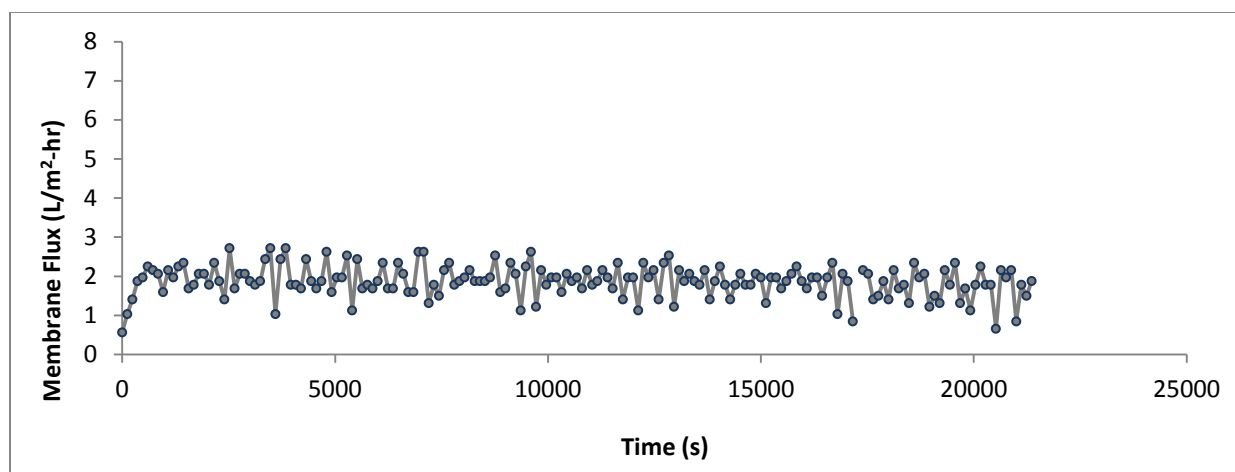


Figure 4-6. Membrane water flux as a function of time. Draw solution: synthetic brackish water; Feed solution: wastewater; Operation time: 6.5 hours.

4.1.2 Effect of the Draw Solution Concentration on the Membrane Flux

The water flux through the FO membrane is directly proportional to the draw solution concentration. The higher the concentration of the solution the higher is the osmotic potential. In order to obtain a higher water flux through the membrane, a high difference in concentration between the feed and draw solution is desired. As the osmotic pressure difference increase, the water flux also increases as shown in equation 1. The greater the difference in osmotic potential, the faster water moves through the membrane. Meanwhile, the osmotic pressure difference across the active layer of the membrane varied gradually during the system operation time. The osmotic potential is high for the concentrated solution and low for the diluted solution. As the dilution of the draw solution occurs, the difference in osmotic pressure gets lower, decreasing the water flux through the membrane.

Several dilutions were made on the draw solution to study the effect of total dissolved solids (TDS) variation on the water flux through the membrane. The experiments were conducted using synthetic water with TDS and salt components similar to the brackish water in Jamestown, VA, to avoid the effects of membrane fouling. The synthetic water quality and salt components are listed in Table 4.1. Figure 4-7 shows the water flux at 10, 25, and 50 percent dilutions of the draw solution. As expected, the water flux decreased as the draw solution got diluted. With a dilution of 10 %, a water flux of approximately 3.2 L/ (m²-hr) was obtained. In the other hand, with 50 % dilution the flux obtained was around 1.0 L/ (m²-hr). However, the flux difference was not significant when the TDS contents were above 25% diluted. This is good for the application of a FO unit on the dilution and reuse of concentrated brackish water. Without membrane fouling, the water flux could be maintained above 2.0 L/ (m²-hr).

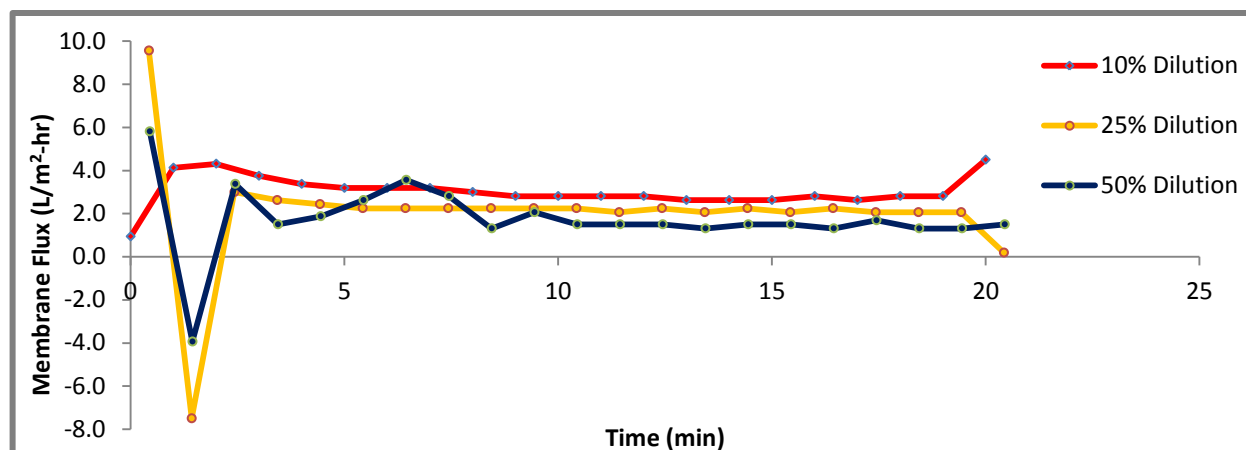


Figure 4-7. Effect of the draw solution dilution on the membrane water flux

Sodium chloride (NaCl) is one of the principal components in the brackish water. See table 3-1 and 3-4 for concentrations of raw brackish water and concentrated brackish water respectively. Past studies have established that as the draw solution gets diluted, the water flow decreases but it is important to determine how NaCl, major component and driving force of the osmotic process, affects the water flux. By doing variations in salt concentration, in this case NaCl at concentrations of 10 g/L, 8 g/L, 6 g/L, and 4 g/L, it was observed that the higher the concentration, the higher the water flux through the membrane. Results are summarized in figure 4-8. The strength of the mixing tendency is measured by the solution's osmotic potential or osmotic pressure. The lower the concentration in the draw solution, the lower the osmotic potential and therefore the lower the water flux through the membrane. But results in figure 4-8 show that even for a low concentration of 4 g/L NaCl, a water flow of approximately 1 L/m²-hr can be obtained. These results are very important in the FO application. Even when the draw solution gets diluted and the osmotic potential gets lower, flux through the membrane still exist. Additional results using other different salts are available in Appendix C.

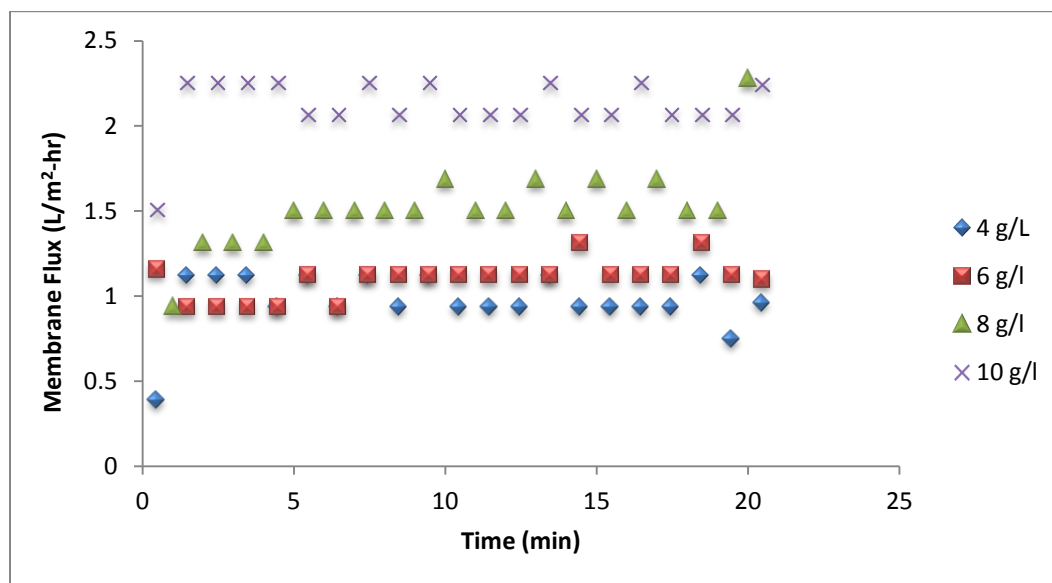


Figure 4-8. Effect of NaCl concentration (10 g/L, 8 g/L, 6 g/L, and 4 g/L) on the membrane flux.

Besides the total dissolved solids (TDS) concentration, different salts may also contribute different amount of osmotic pressure. Because brackish water is composed by different salts, it is important to determine how each salt affect the FO process. The molality as well as the dissociation factor affects the osmotic pressure on each one of the salts. The osmotic pressure is given by the equation:

$$\Pi = iMRT \quad (2)$$

where Π is the osmotic pressure, i is the van't Hoff factor, M is the molality, R is the gas constant, and T is the absolute temperature.

In order to study the effect of the different salts in the membrane flux, NaCl, CaCl₂, NaHCO₃, and Na₂SO₄ at a concentration of 10 g/L were used as the draw solutions. Results of

the water flux for each salt are shown in figure 4-9. Based on these results it can be observed that of all salts that comprise the brackish water, NaCl is the one that has the most impact on the membrane flux. For all of the tested salts, a water flow higher than $1 \text{ L/m}^2\text{-hr}$ was obtained.

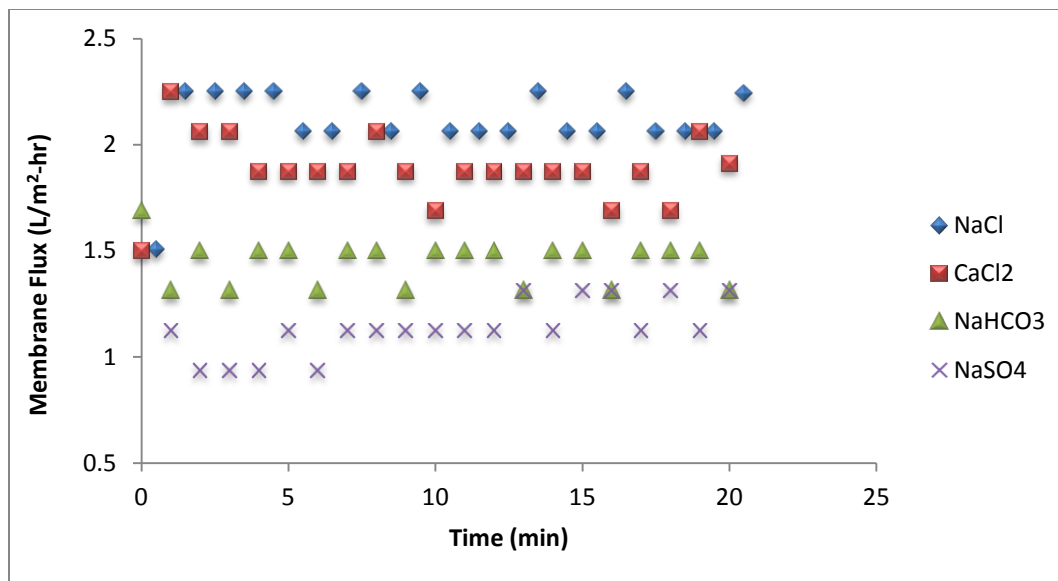


Figure 4-9. Effect of NaCl, CaCl₂, NaHCO₃, and NaSO₄ on the membrane flux at a concentration of 10 g/L.

The osmotic pressure of each salt was calculated using equation 2. Results show that NaCl has the highest osmotic pressure and NaSO₄ the lower osmotic pressure. This results support the different water fluxes obtained in the experiment. Calculations and results are summarized in Appendix D.

The gradual dilution of the draw solution is not the only factor that affects the water flux through the membrane. Water quality and conditions such as pH, temperature, turbidity, and organic matter play an important role on the membrane flux. The membrane flux was studied under different conditions using brackish water as the draw solution and wastewater as the feed solution. Figure 4-10 shows the membrane flux obtained by making variations in water turbidity, pH, and temperature. For each variation the water flux remained stable between 2.5 and 1 L/m²-hr. After 4 days (6000 min) of operation, using the same membrane, there was no observed flux decline due to fouling or any other factor affecting the membrane.

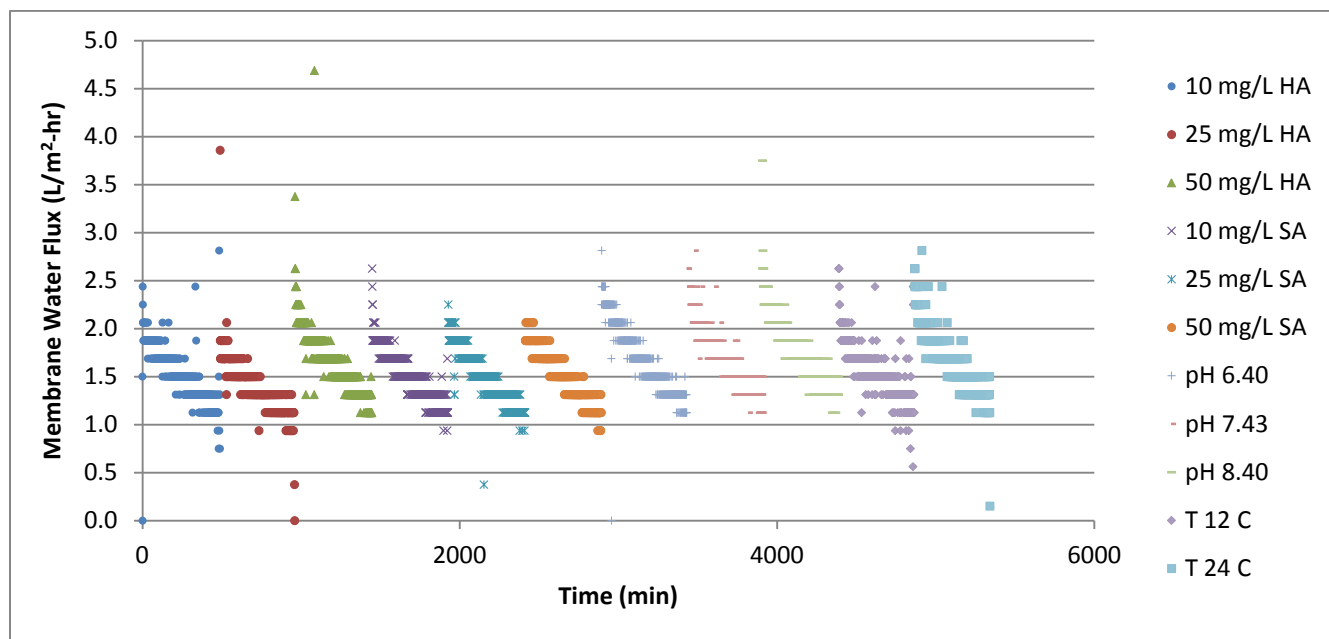


Figure 4-10. Membrane flux obtained for each variation (pH, temperature, and turbidity) in experimental conditions.

4.1.3 The effect of temperature on membrane flux

A variation on the feed solution temperature was made in order to study its effect on the membrane water flux. As the temperature of the water increased from 10°C to 60°C, an increase in the water flux from 1 L/m²-hr to 3 L/m²-hr was observed as shown in figure 4-11. Higher temperatures in either solution feed or draw, increase the water flux through the membrane. The obtained linear regressions for the feed and draw solution are shown in figure 4-12 and 4-13 respectively. Based on these results, the membrane flux is directly proportional to temperature. This relation is given by the van't Hoff equation:

$$\Delta\pi = CRT \quad (2)$$

where $\Delta\pi$ is the osmotic pressure, R is the gas constant, T is the absolute temperature, and C is the molar concentration. Van't Hoff established that the osmotic pressure is proportional to the absolute temperature.

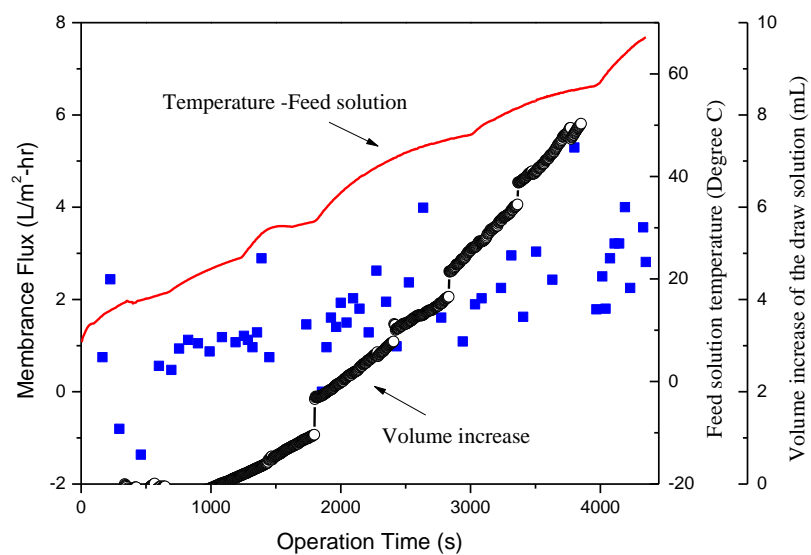


Figure 4-11. Membrane flux and volume increase of the draw solution as a function of feed solution temperature.

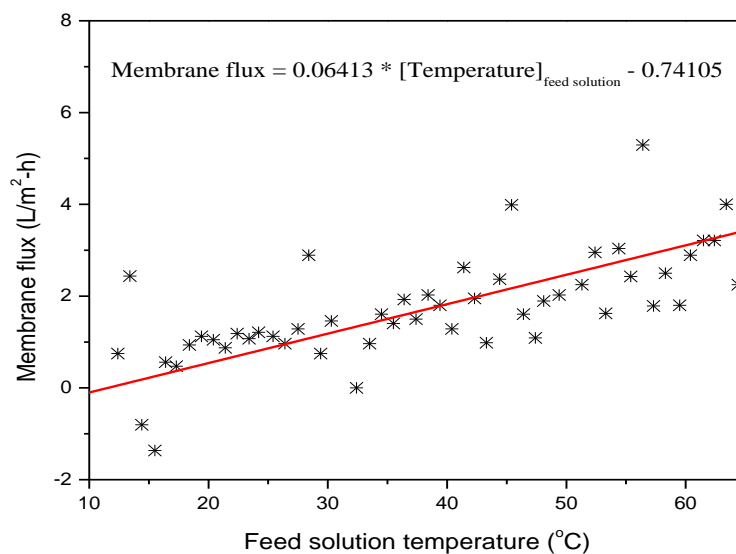


Figure 4-12. Effects of Feed solution temperature on membrane flux.

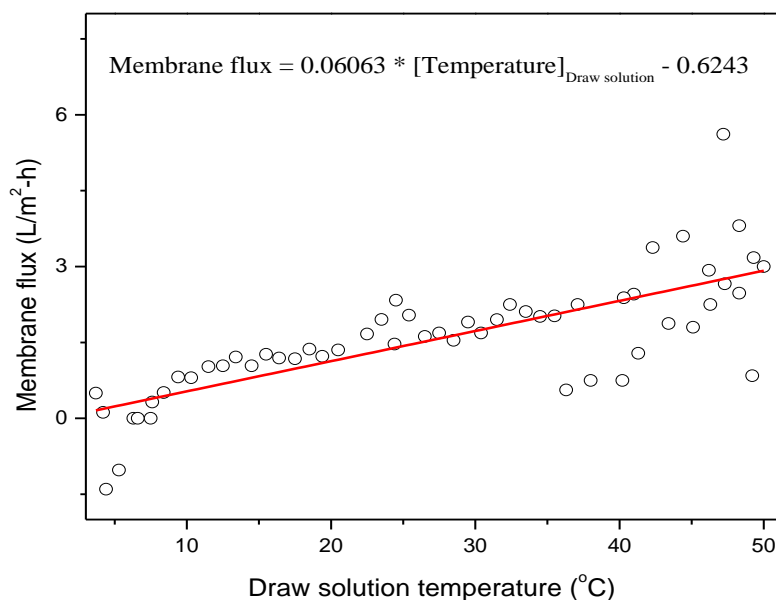


Figure 4-13. Effects of Draw solution temperature on membrane flux.

As previously discussed, temperature has an effect on the membrane flux. The higher the temperature, the higher the water flux through the membrane. Temperature has an impact on the osmotic pressure making it increase with a rise in temperature (equation 2). Feed solution at temperatures of 5 °C, 12 °C, and 24 °C was also study to determine the temperature impact on the membrane flux. As shown in figure 4-14, at a temperature of 24 °C the highest flux was obtained in comparison with the other two temperatures. The water flux was between 1 and 2 L/m²-hr approximately. These results are very similar to those obtained in previous experiments.

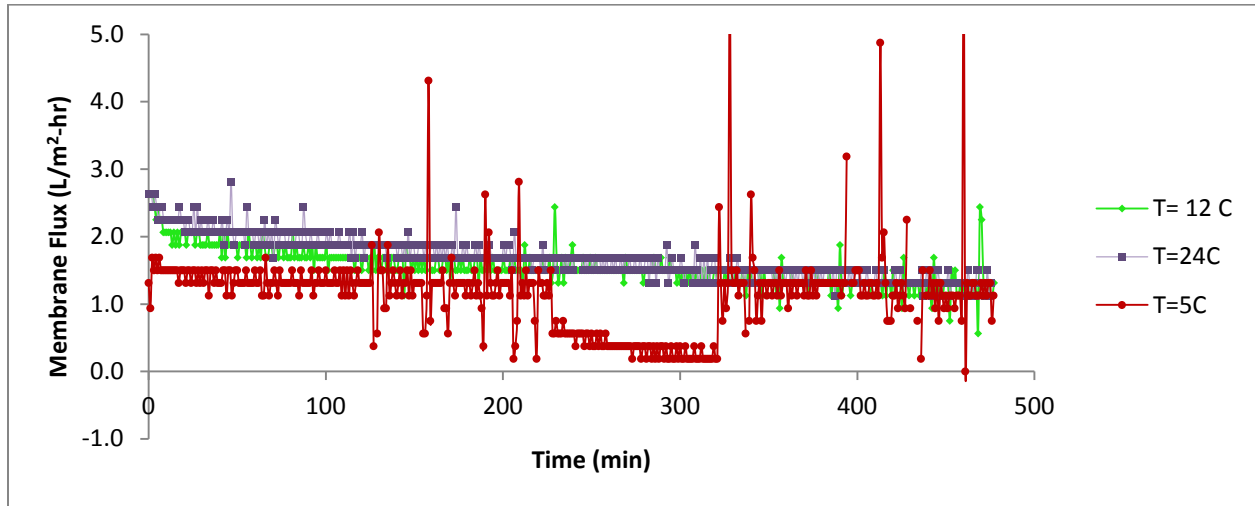


Figure 4-14. Effects of Feed Solution temperature on membrane flux. Experimental condition: Wastewater – feed solution; Brackish Water- draw solution.

Because osmotic pressure difference is directly proportional to the absolute temperature, an increment in temperature will be reflected in the osmotic pressure difference which will also be reflected in the water flux through the membrane. Equation (1) and equation (2) can be combined to establish a direct relation between water flux and the absolute temperature resulting in equation (3).

$$J_w = A (\sigma \Delta \pi - \Delta P) \quad (1)$$

$$\Delta \pi = CRT \quad (2)$$

$$J_w = A (\sigma (CRT) - \Delta P) \quad (3)$$

4.1.4 The effect of pH on membrane flux

Braghetta and DiGiano in 1997 established that the volume of absorbed water in the electrolyte membrane is a function of pH and ionic strength. At high pH and/or low ionic strength, the charged functional groups in the membrane matrix force adjacent polymers apart, thus increasing water permeability. These same conditions would also favor an increased thickness of the diffuse double layer and therefore greater rejection of charged solutes. On the other hand, at low pH or high ionic strength, the charge of the membrane matrix is reduced or shielded and membrane polymers come closer to one another, thus reducing water permeability. This also results in reduction of the diffuse double layer thickness, and therefore diminished rejection of charged solutes [30].

Related to pH, it is hypothesized that the electrostatic repulsion between ionisable functional groups of the membrane polymeric matrix increases as the solution pH increase, thereby leading to an increased average pore size and higher permeate flux. Indeed, both the active layer and the supporting layer became more negatively charged with increasing feed solution pH. In order to study the effect of pH on the proposed FO process, further experiments were made using brackish water and wastewater as the draw and feed solution, respectively. A CTA membrane with a tolerance pH range of 2.0 to 12.0 was used throughout the experiments.

The pH of the wastewater was manipulated to values of 6, 7, and 8 in order to study its effect on the membrane flux. In figure 4-15 one can observe that the membrane flux was between 1 and 2 L/m²-hr for the three different pH values that were tested for a period of time of approximately eight (8) hours. The difference in membrane flux for each pH is not significant

although the highest flux was obtained at the highest pH (pH=8). Based on this results pH have little effect over the membrane flux.

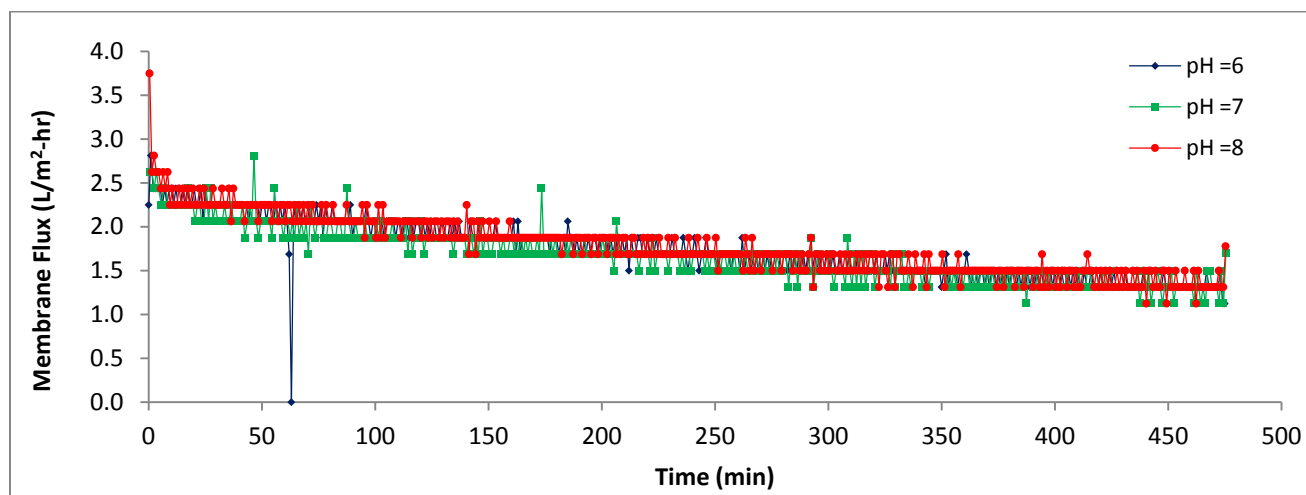


Figure 4-15. Effect of pH on the membrane flux. Experimental conditions: Draw solution-brackish water; Feed solution- wastewater.

In previous experiments the focus of the experiment was to study how the pH of the feed solution affected the membrane flux. Moreover it is important to determine if the pH of the draw solution itself have any effect on the membrane flux. By changing pH of the draw solution, it was observed that the water flux through the membrane was stable between 1 and 2 L/m²-hr. No significant changes occurred. Results are shown in figure 4-16. Comparing these results with those obtained by changing the pH of the feed solution (figure 4-17), there is not a significant difference on the membrane flux.

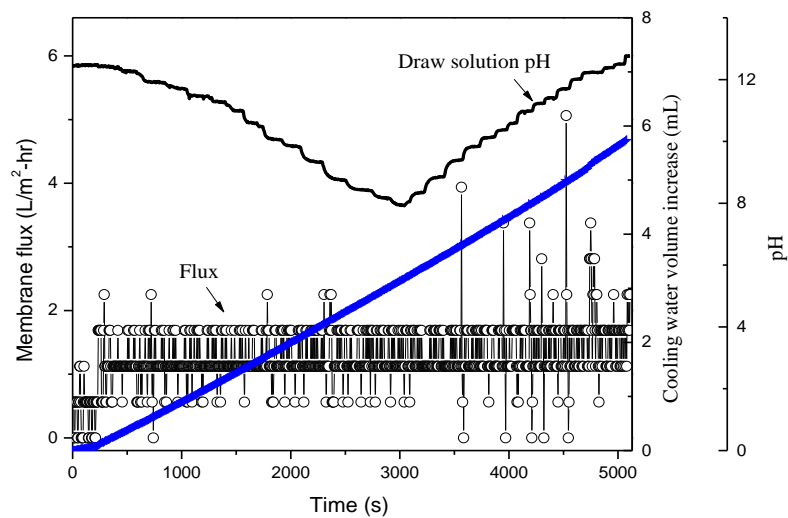


Figure 4-16. Draw solution pH variation effect on membrane flux and the total volume increase of the draw solution.

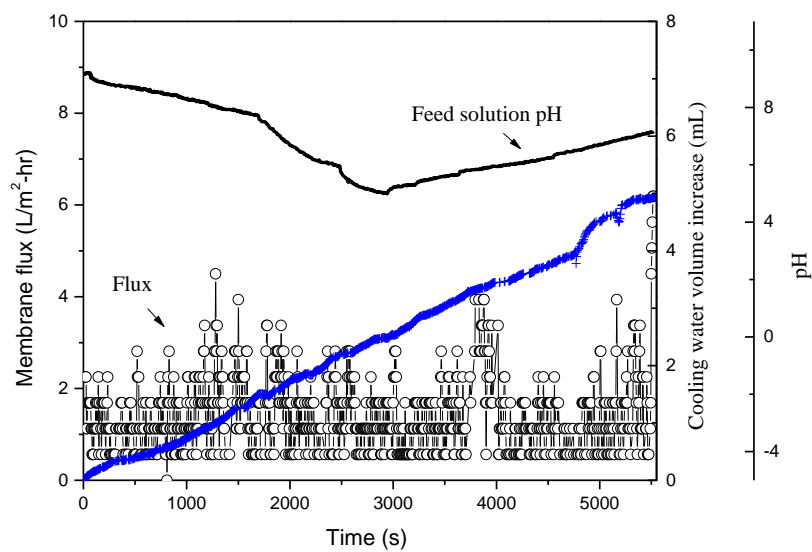


Figure 4-17. Feed solution pH variation effect on membrane flux and the total volume increase of the draw solution.

4.2 Reverse Salt Flux Through the FO Membrane

4.2.1 Conductivity

The effects of operation time on the conductivity, TDS, and dilution of the draw solution was examined. Distilled water and 10 g/L NaCl were used as feed solution and draw solution respectively. Figure 4-18 shows that after 2.5 hrs the conductivity in the feed solution increased. This may be caused by the reverse salt flux coming from the draw solution into the feed solution. Because pure water is leaving the feed solution, an increase in TDS is observed. As time pass, the feed solution gets more concentrated and an increment in the draw solution volume is also observed. As pure water goes through the membrane, the draw solution gets diluted. The water flux through the membrane was constant with an average flux of approximately 3 L/m²-hr.

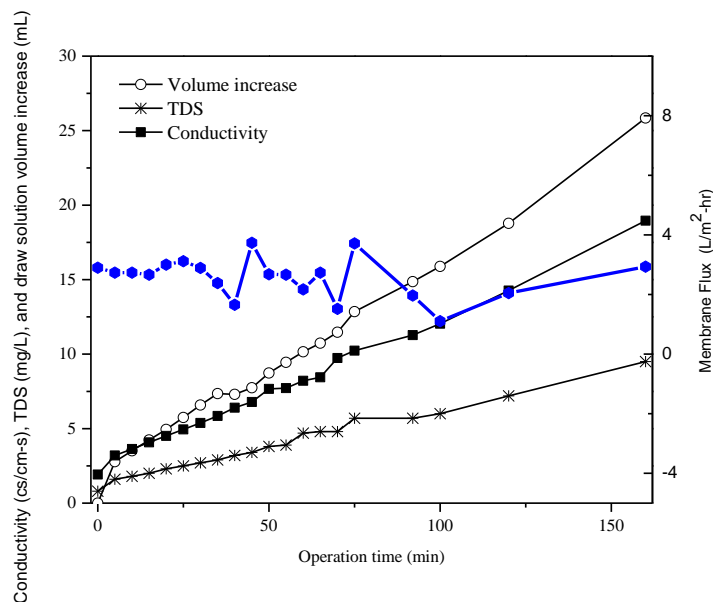


Figure 4-18. Conductivity, TDS, draw solution volume increase, and membrane flux as a function of time.

The conductivity in the feed solution is directly proportional to the volume increase of the draw solution. The direct relation can be observed in figure 4-19. The higher the water flux through the membrane the higher the conductivity in the feed solution. As the pure water pass through the membrane from the feed solution into the draw solution, salt also pass through the membrane but in the opposite direction, from the draw solution to the feed solution. This process is very common when using membranes and it is known as reverse flux.

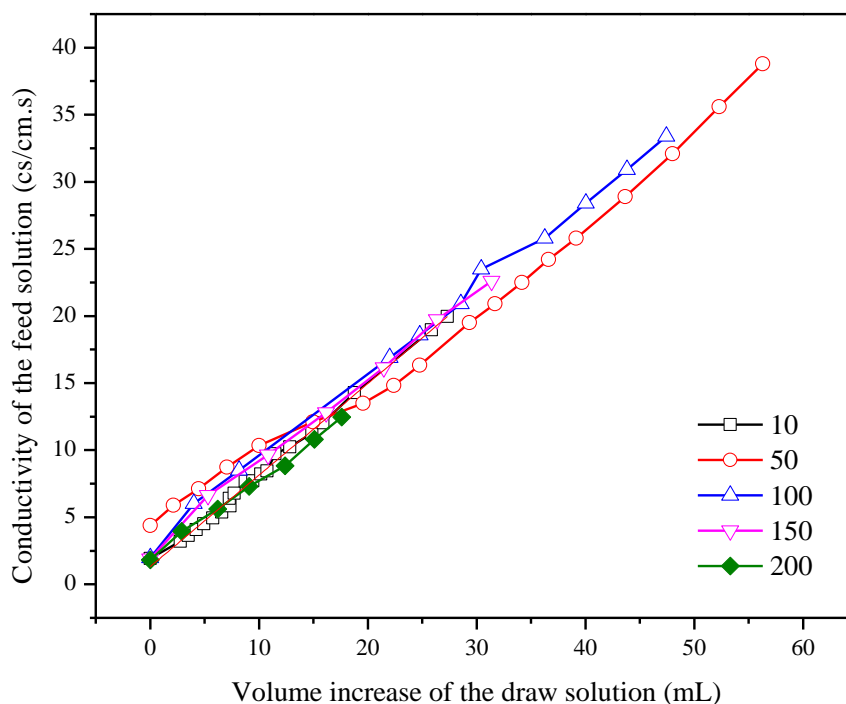


Figure 4-19. Relation between the conductivity of the feed solution and the volume increase of the draw solution with variations on draw solution concentration.

Because of the reverse salt flux, the conductivity in the feed solution (wastewater) increases with time. Results are plotted in figure 4-20. A relation between the conductivity of the feed solution and the increase in volume of the draw solution was established. A linear equation

conductivity = 0.632*volume increase_{draw solution} + 2.227 was obtained as observed in figure 4-19. Conductivity is directly proportional to the dilution of the draw solution which means that as water flow through the membrane into the draw solution, salt is also passing through the membrane into the feed solution.

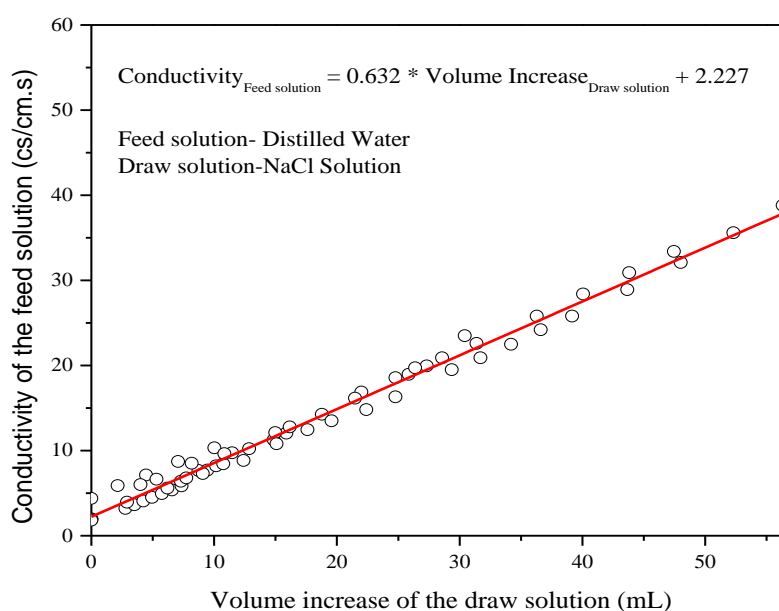


Figure 4-20. Relation between the conductivity of the feed solution and the volume increase of the draw solution.

4.3 Pollutants rejection and membrane fouling on forward osmosis

4.3.1 Organic and Inorganic Matter Removal in Forward Osmosis

The rejection of organic and inorganic species by charged membranes is thought to be controlled not only by physical constraints of pore size, but also by conditions of solution chemistry and the chemical properties of the membrane surface [27]. Negatively charged membranes have been shown to repulse negatively charged ions from the surface and thus reduce membrane fouling due to solute adsorption and pore plugging [28]. Through the examination of the sizes of the target organisms and the range of membrane pore sizes, it is apparent that removal of these organisms is specific to the particular membrane and its pore size distribution, when considering the membrane as a simple physical barrier. It is important to note that other physical/chemical mechanism also play a role in the removal of microorganism [29].

One of the advantages of the FO membrane is the high percent of rejection to different micropollutants that are present on impaired water. Hancock et al. investigated water permeation and NaCl rejection for the CTA. They found that FO membrane have a NaCl rejection percent of 93.2 ± 0.9 . During the same study, it was found that by using FO as an advanced pretreatment for RO a rejection percent of more than 99 % can be achieved [23].

The transport of organic matter was evaluated using ultraviolet absorbance 254nm. Continuous UV254 data of the draw solution (synthetic brackish water) was monitored throughout the experiment when wastewater was used as the feed solution. The absorbance increased slightly from 0.195 cm^{-1} to 0.211 cm^{-1} in a five (5) hours operation period, indicating

that the membrane used in this study provided a good organic matter rejection. Results are shown in figure 4-21.

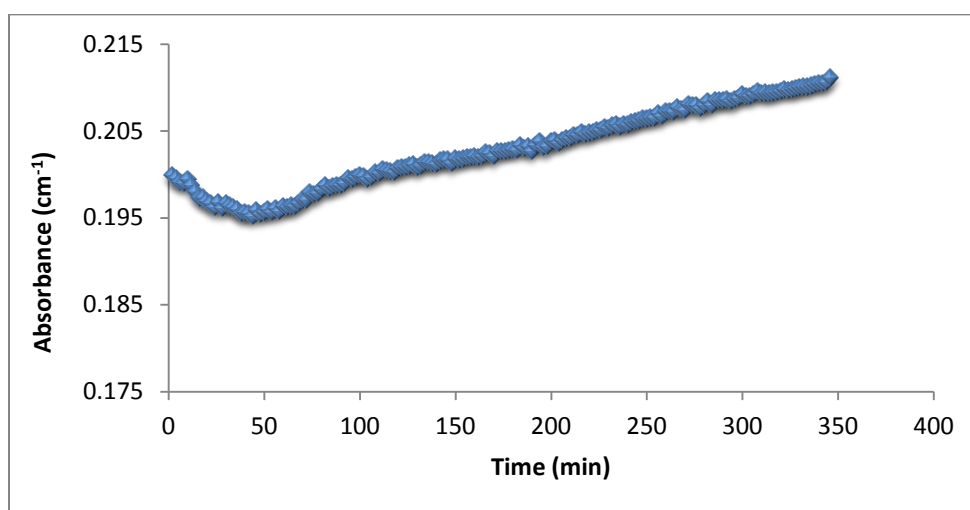


Figure 4-21. Draw solution (brackish water) absorbance as a function of time

Further experiments were performed but this time using real brackish water as the draw solution. After eight hours the system running, the increment in absorbance on the brackish water was of 0.089 cm⁻¹. Base on this results, shown in figure 4-22, FO membrane have a good pollutants rejection in a short period of running time.

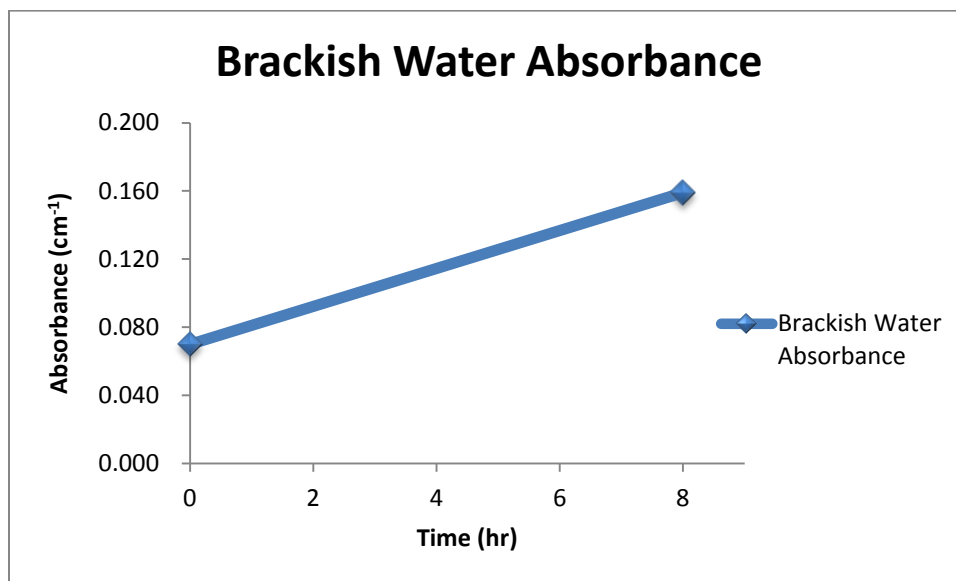


Figure 4-22. Absorbance data for brackish water after 8 hours system operation.

Organic matter, sodium alginate and humic acid, were added at three different concentrations (10 g/L, 25 g/L, 50 g/L) into the wastewater with the objective of investigating how effective is the FO membrane to the rejection of pollutants. The initial absorbance for the brackish water was of 0.054 cm^{-1} . UV_{254} data for brackish water was collected and analyzed after 8 hours of operation for each concentration of organic matter. Increments in the absorbance of the brackish water are shown in table 4-2. As results show, FO membranes have a good pollutant rejection. After 8 hours the highest increment in absorbance was of 0.035 cm^{-1} when 50 g/L of humic acid was added to the feed solution which means that the membrane showed less rejection for humic acid than for the other matter.

Table 4-2. Brackish Water Absorbance after Adding Organic/Inorganic Matter

Increase in Absorbance on Brackish Water after 8 hours Running System			
Compound [g/L]	10	25	50
Sodium Alginate	0.025	0.016	0.016
Humic Acid	0.025	0.032	0.035
Kaolin (turbidity)	0.041	0.017	0.016

Further experiments were made in order to study the membrane pollutants rejection with variations on the feed solution. First, the pH was adjusted to values of 6.4, 7.4, and 8.4. In table 4-3 can be observed that absorbance for the brackish water was the same for all pH values. Compared to the initial absorbance (0.054 cm^{-1}), an increase of 0.013 cm^{-1} was observed after 8 hours running. Meanwhile, temperature was adjusted to 5°C and 10°C . The observed increase in absorbance was insignificant.

Table 4-3. Brackish Water Absorbance after Variations on pH and Temperature

Increase in Absorbance on Brackish Water after 8 hours Running System	
pH	Absorbance (cm^{-1})
6.4	0.013
7.4	0.013
8.4	0.013
Temperature	Absorbance (cm^{-1})
5 °C	0.020
10 °C	0.011

4.3.2 Membrane Fouling

Organic foulants can accumulate on the membrane surface creating a fouling layer. Fouling can increase the resistance to water transfer through the membrane. In the current study we evaluated the impact of the composition of the feed solution (treated wastewater) on the membrane. The objective was to identify if wastewater foulants were deposited on the membrane surface. A long time operation study was performed continuously for a period of 23 hours. The water flux was monitored during the experiment. The membrane flux was stable around $1 \text{ L/m}^2\text{-hr}$. There was no observed flux decline due to membrane fouling. Results are plotted in figure 4-23. One of the advantages of FO is that membrane fouling problems can be avoided.

Implementing FO as an advanced RO pre-treatment can help protect the membrane from scaling and fouling. Both processes will act as a dual barrier against pollutants.

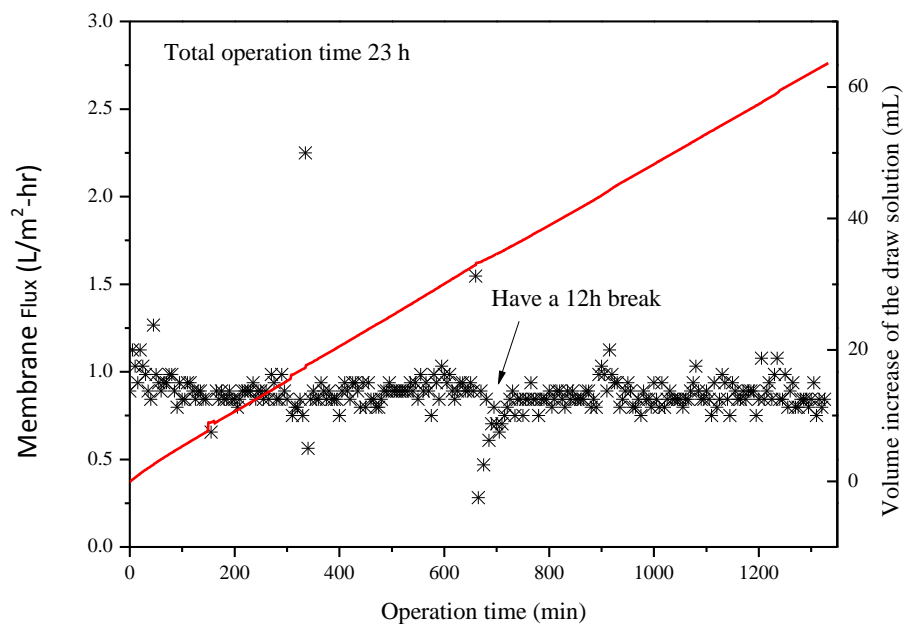


Figure 4-23. Effect of long time (23 hours) operation on membrane flux and dilution of the draw solution.

One of the objectives of this study was to observe the effect of organic and inorganic matter on the FO membrane fouling. Kaolin and Sodium alginate were used as the inorganic and organic foulant respectively. After 10 hrs of operation, the water flux through the membrane was stable with an average flow of $1 \text{ L/m}^2\text{-hr}$ and $0.6 \text{ L/m}^2\text{-hr}$ for the inorganic and organic foulant respectively. Figure 4-24 and 4-25 shows that there was minimal flux decline due to high turbidity on the membrane surface.

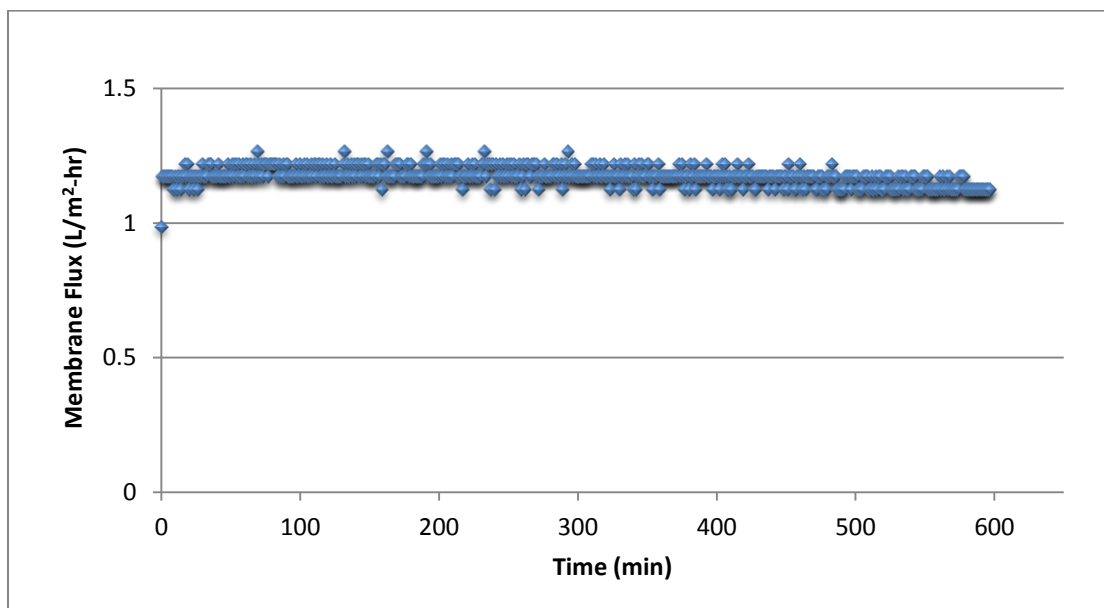


Figure 4-24. Effect of inorganic matter on membrane flux; Inorganic foulant –Kaolin; Operation time-10hrs.

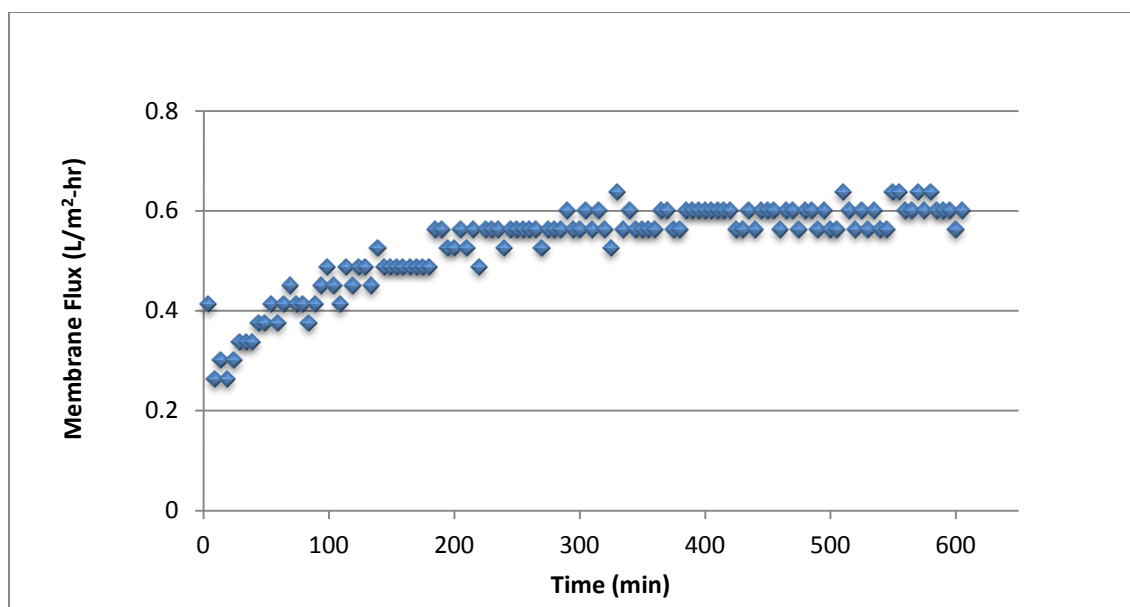


Figure 4-25. Effect of organic matter on membrane flux; Organic foulant -Sodium Alginate; Operation time-10 hrs.

4.4 Disinfection Byproduct Rejection through FO

Disinfection of wastewater is required before treated wastewater is discharged into natural water bodies. It has been known that chlorine reacts with aquatic organic matter or disinfection byproduct precursors, to form possibly carcinogenic DBPs. The performance of treatment processes has a significant impact on the removal of wastewater organics. That's why the concentrations of DBP (THMs and HAAs) species show variances among different wastewater effluents.

The maximum contaminant levels of DBPs for drinking water are 0.080 mg/L and 0.060 mg/L for THMs and HAAs, respectively. Meanwhile, NPDES discharge limit only regulate some THMs (chloroform) in wastewater treatment plants (WWTPs). DBPs in wastewater have not yet received much attention because WW is not to be consumed by human. Effluents from wastewater treatment plants (WWTPs) containing disinfection byproducts (DBPs) could be utilized downstream as a potable water supply or as a possible water source for drinking water source. Investigations on the DBP formation during wastewater disinfection are an important research area.

The system was running for an eight (8) hour period using brackish water and wastewater as the draw and feed solutions respectively. In order to determine THM and HAA concentration in the diluted brackish water, samples of 40 mL were taken at time zero and after eight hours of operation. This was made in order to determine the disinfection byproduct rejection through the forward osmosis membrane.

The pH effect on DBP removal through the FO membrane was also examined. Variations in pH from 6 to 8 were made. Samples for each pH were taken and properly analyzed. Because temperature has a significant effect on disinfection byproducts, a study of the effects of temperature on DBP removal through the FO membrane was made. DBPs were monitored at different temperatures in a range from 5 °C to 23 °C. The effect of organic matter in DBP membrane rejection was also investigated. Kaolin and Humic Acid were used as organic and inorganic matter in concentrations of 10, 25, and 50 mg/L.

Wastewater was analyzed using gas chromatography technique in order to determine the concentration of DBPs. It was found that wastewater had an initial concentration of 101 µg/L THMs and 15.4 µg/L HAAs. Taking these values into consideration, the rejection percents were calculated in next sections.

4.4.1 Effect of pH on DBPs membrane rejection

Several studies have proved that water pH has an impact on disinfection byproduct formation. It is generally believed that the reaction mechanism leading to the formation of THMs is based catalyzed, meaning the reaction is catalyzed by hydroxide ions (OH^-) present in the water and therefore proceeds faster at more alkaline pH values (Rook, 1977). In the other hand, the formation of HAAs is enhanced under acidic conditions [39]. pH condition not only affect DBP formation but also the rejection mechanisms of the membrane.

High pH conditions on the CTA membrane increase the thickness of the diffused layer and therefore greater rejection of charged solutes can be observed [30]. High rejection can be explained by electrostatic exclusion between anionic compounds and the negatively charged

membrane. As mention before, low ionic strength promotes a higher flux and greater rejection of solutes [32].

Figure 4-26 and 4-27 shows DBP concentrations for THMs and HAAs available in the wastewater and also the concentration found in the brackish water after 8 hours of operation, respectively. Considering the change in pH, it is a minor factor affecting the DBPs rejection percent. THMs the rejection percent at a pH of 6.4, 7.4, and 8.4 was around 94 %. It was very consistent throughout all the pH values. Meanwhile, for HAAs the rejection percent was around 60 %. Furthermore, rejections percents available in table 4-4 show that for HAAs the rejection percent decreases from 64.3 % to 50.6% as the pH increases from 6.4 to 8.4, respectively.

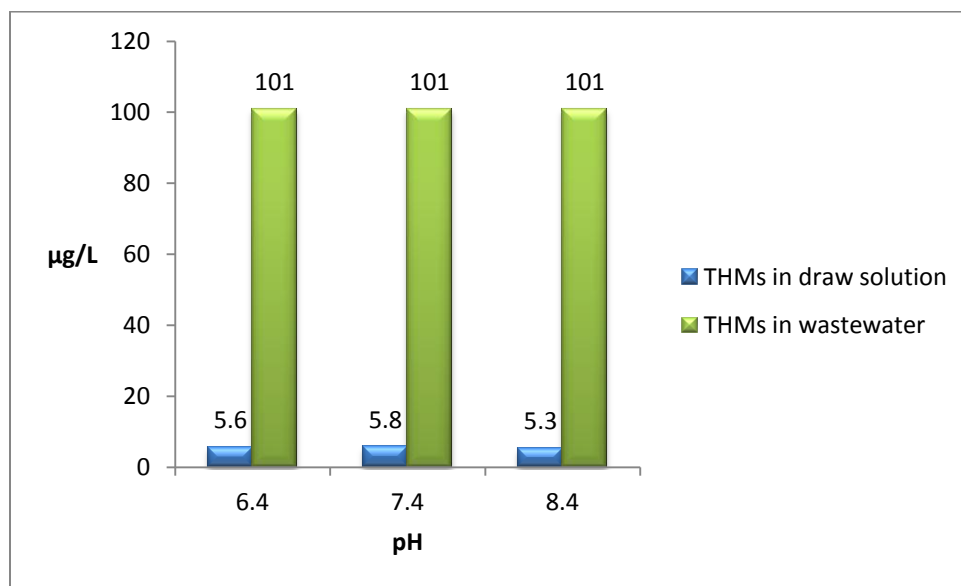


Figure 4-26. pH effect on THMs membrane rejection

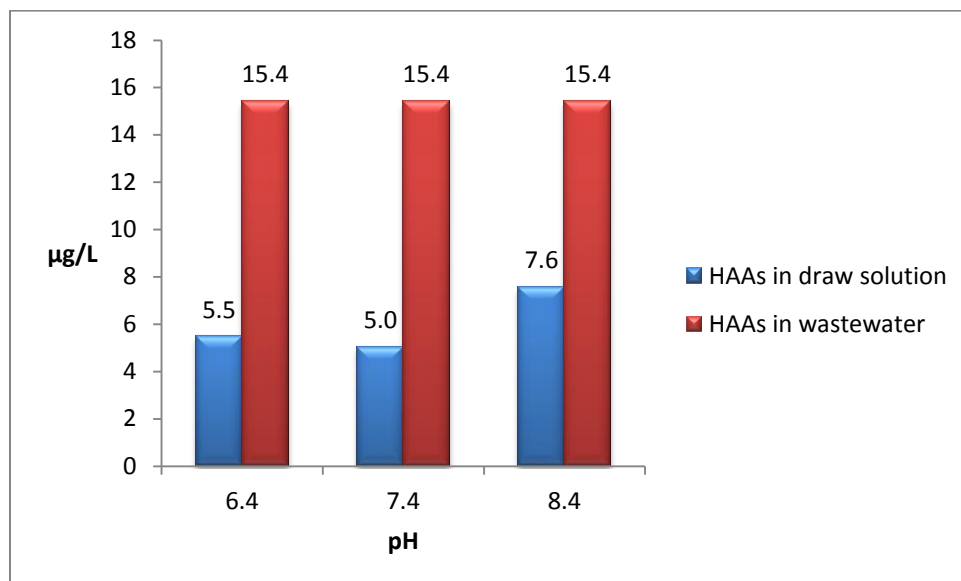


Figure 4-27. pH effect on HAAs membrane rejection

4.4.2 Effect of temperature on DBPs membrane rejection

Water temperature has a significant impact on DBP formation. Increasing water temperature could enhance the formation rates of disinfection byproducts [24]. It is also known that increasing the solutions temperature increase the water flux through the membrane.

The temperature on the feed solution was manipulated three (3) times in order to study its effect on DBP rejection through the FO membrane. Temperatures were kept below 25 °C in order to avoid a significant influence on the membrane structure although the CTA membrane can withstand temperatures around 45 °C. Figure 4-28 shows the initial THM concentration present in the wastewater and the THM concentration present on the draw solution after eight hours of operation. As shown in table 4-5, a 94 % rejection was obtained for all three temperatures. THM membrane rejection was insensitive to temperature variations.

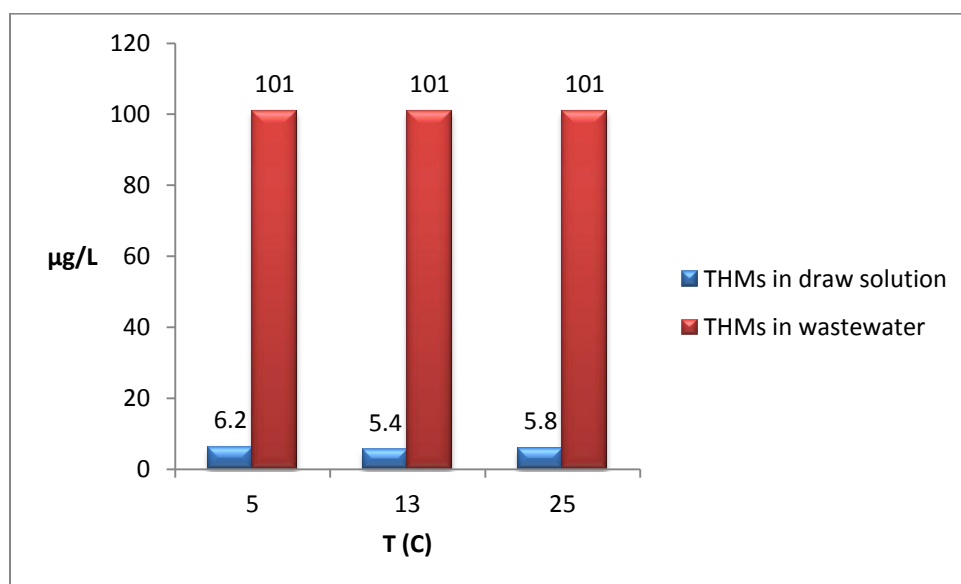


Figure 4-28. Temperature effect on THMs membrane rejection

Figure 4-29 shows the results for HAA concentration on the feed solution and also on the draw solution after eight hours of operation. The membrane rejection percents for HAAs at three different temperatures are summarized in table 4-5. For HAAs an average rejection of 69.7% was obtained.

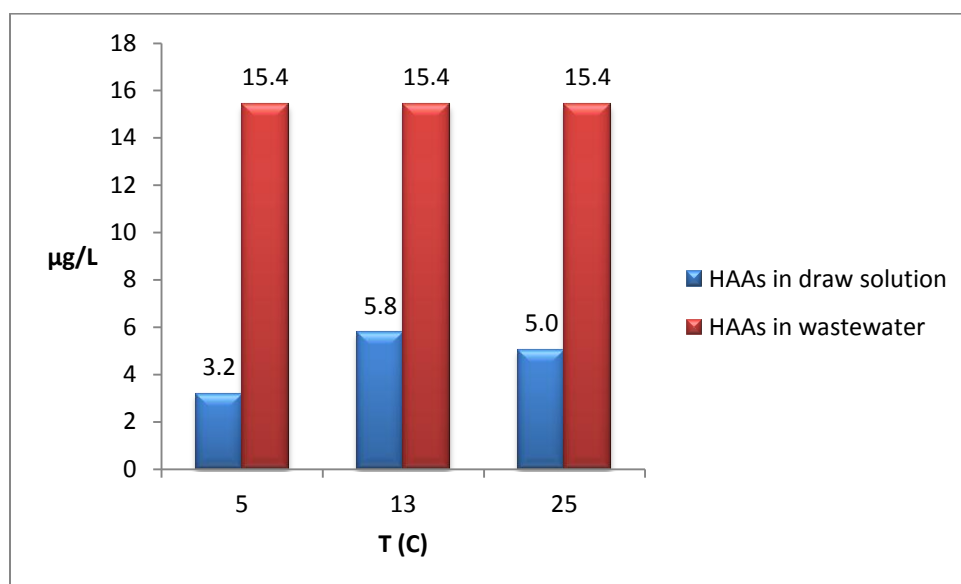


Figure 4-29. Temperature effect on HAAs membrane rejection

Table 4-4. pH Effect on DBPs FO Membrane Rejection

Membrane % Rejection			
pH	6.4	7.4	8.4
THMs	94.5	94.3	94.8
HAAs	64.3	67.5	50.6

Table 4-5. Temperature Effect on DBPs FO Membrane Rejection

Membrane % Rejection			
Temperature	5 °C	13 °C	25 °C
THMs	93.9	94.7	94.3
HAAs	79.2	62.3	67.5

4.4.3 Effect of initial DBPs contents on the water flux through the FO membrane

The objective of this experiment was to observe how the concentration of DBPs present in the wastewater affect the membrane flux. DBP concentrations may show variances among different WWTP. The performance of treatment processes have a significant impact on DBP formation. Secondary wastewater effluent was used throughout the experiment with initial concentration of 15 µg/L and 101 µg/L of HAAs and THMs, respectively. Additions of 100 µg/L and 200 µg/L of DBPs were made in order to put into perspective that depending on the WWTP performance, DBP concentration will be different.

Figure 4-34 shows that water flux decreases with higher concentrations of DBPs in the wastewater. Looking at figure 4-35 one can also observe that with either, high or low concentration of DBP present in the feed solution, the membrane flux was maintained over 1 L/m²-hr after eight (8) hours of operation. The presence of DBPs in the feed solution is a minor factor affecting the membrane flux.

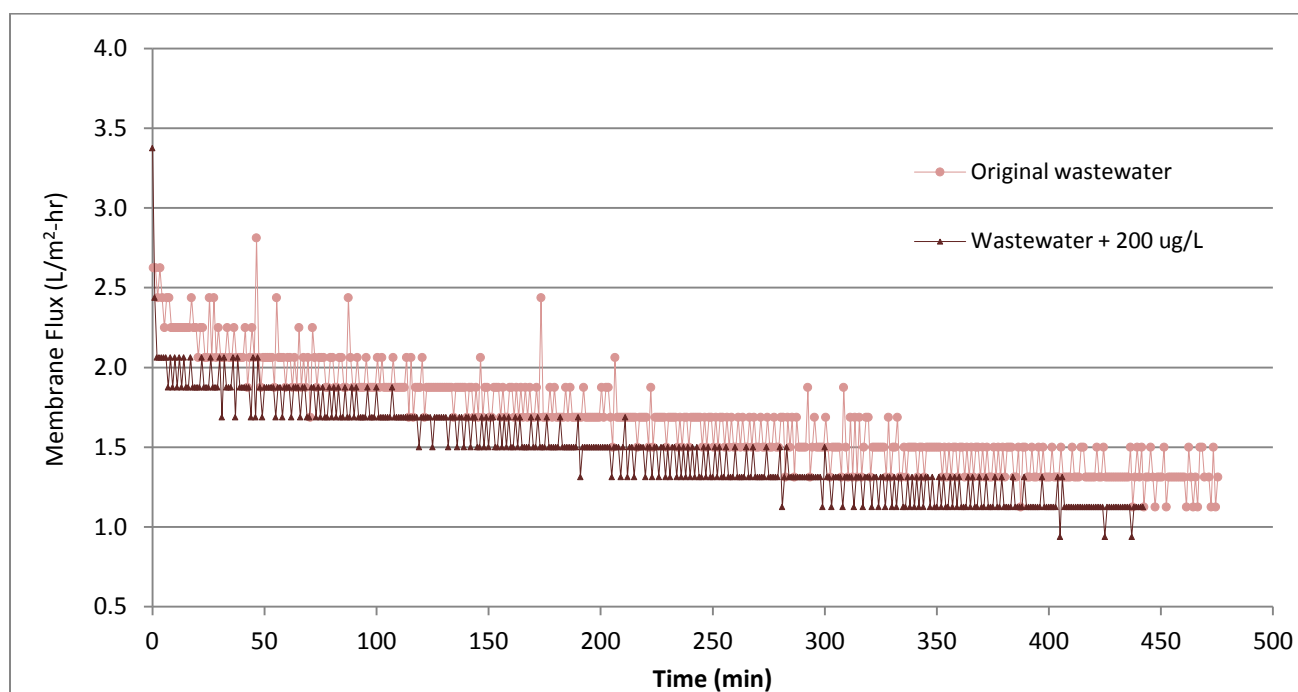


Figure 4-30. Membrane water flux obtained using regular wastewater and wastewater with the addition of 200 µg/L of DBPs. The membrane flux was monitored and recorded after the addition of 200 µg/L of DBP into the feed solution (wastewater).

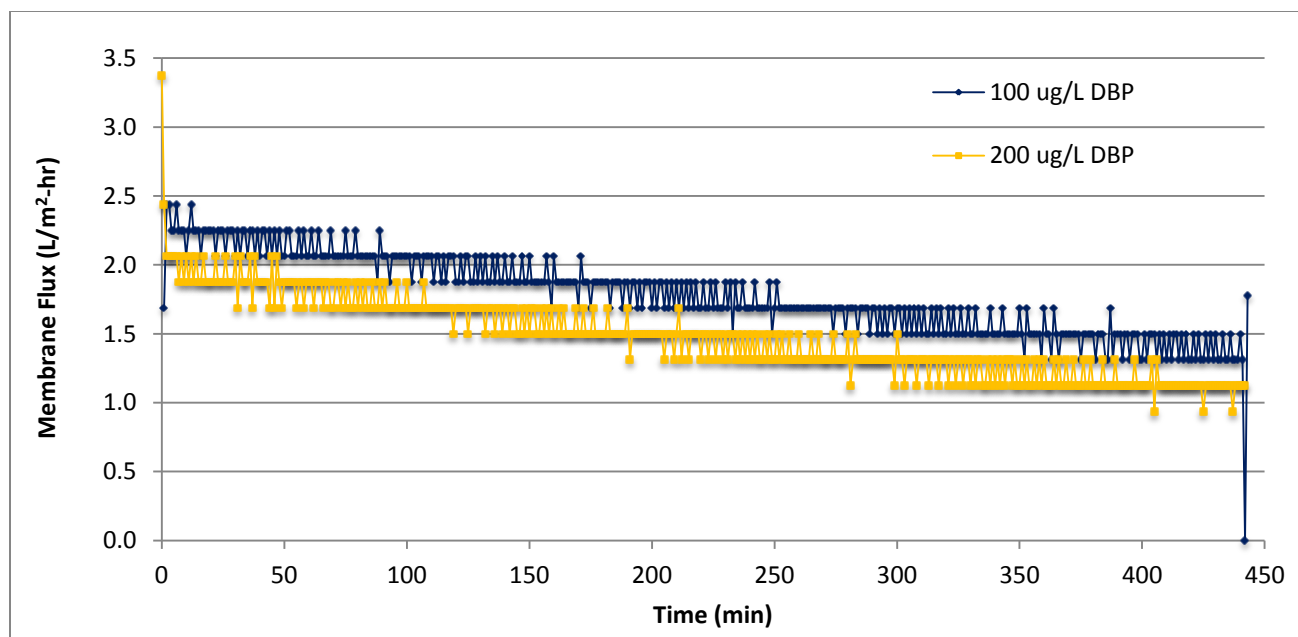


Figure 4-31. Effect of DBP concentration on the membrane flux. The membrane flux was monitored and recorded individually after the addition of 100 and 200 µg/L of DBP into the feed solution (wastewater).

Chapter 5

Conclusions

In this study we evaluated the feasibility of forward osmosis as a pre-treatment for a reverse osmosis desalination process. During the implementation of forward osmosis (FO) for the treatment of highly salt-concentrated brackish water from a reverse osmosis process, the concentrated stream was diluted using secondary treated wastewater. The diluted brackish water can be reused in the process reducing the energy consumption required by the reverse osmosis (RO) system. FO system can also help to reduce substantially the volume of the concentrate that is discharged into water bodies. The following experimental results were obtained in our study:

(1) The average membrane flux was approximately $2.0 \text{ L/m}^2\text{-hr}$. The membrane flux is directly proportional to the temperature. As the temperature of the feed solution increase the membrane flux also increases. Compared to temperature, both pH and turbidity of the feed solution have little effect on the membrane flux.

(2) Organic and inorganic matters were added to the feed solution to study the membrane rejection. The UV_{254} of the draw solution brackish water was monitored throughout the experiments and increased slightly from 0.195 cm^{-1} to 0.211 cm^{-1} , indicating that the FO membrane used in this study provided a good organic matter rejection.

(3) In the system with organic matter addition to the feed solution, the membrane flux was studied and it was observed that the flux was stable between 2.5 and $1 \text{ L/m}^2\text{-hr}$. During the

long time operation (23 hours), there was no observed flux decline due to membrane fouling, even for water with high turbidity (50 mg/L kaolin). The FO membranes protect the RO membranes from fouling and scaling which helps in energy saving.

(4) The rejection of disinfection byproducts (DBPs) through the FO membrane was also studied. For THMs, the rejection percent through the membrane was around 94%. On the other hand, for HAAs the rejection percent varied from 62 % to 80%.

(5) Implementing FO as a RO pre-treatment helps protect the membranes from scaling and fouling. Combining FO with the existing RO desalination process will act as a dual barrier for the impaired water removing micropollutants and exceeding the rejections percents obtained throughout this investigation.

Based on this study, forward osmosis implemented as a RO pre-treatment is a potential technology not only for the treatment of concentrated brackish water but also for recycling and reuse impaired water. Further experiments need to be done to improve and optimize the process. More studies may need to be done in order to determine if the dual barrier system is capable of producing drinkable water by treating impaired water.

Future Work

- Study FO membrane life as a function of the feed water source, frequency of cleaning, system design, and operating conditions.
- Study how the physical-chemical properties of the FO membrane (pore size, water permeability, charge, etc.) affect the pollutants rejection.
- Study how the physical-chemical properties of DBP precursors and other compounds affect FO membrane rejection.
- Investigate the rejection of DBPs precursors through FO membrane.
- Perform a pilot-scale experiment using both RO and FO systems to determine the effluent water quality, energy savings, and overall percent of pollutants removal. Study the fresh water obtained from the process. Analyze water quality and parameters in order to determine if it can be used as drinking water under the state and EPA regulations.
- Implications of using impaired water as drinking water
 - Public acceptability
 - Analyzed the need of new and more advanced technology which helps improve treatment efficiency and quality assurance.
 - Develop a better understanding of contaminants and how to obtain a good removal through the process.

Bibliography

- [1] Cath, T.Y., Childress A.E., Elimelech M. (2006). Forward osmosis: principles, applications, and recent developments. *Journal of Membrane Science*, 281, 70-87.
- [2] Miller, J.E., Evans, L.R. (2006). Forward osmosis: a new approach to water purification and desalination. *A report prepared by Sandia National Laboratories Albuquerque, NM*.
- [3] Salter, R.J. (2006). Forward Osmosis. *Water Conditioning & Purifications*, pp36-38.
- [4] Water Quality Issues: Natural Gas Drilling and Marcellus Shale
- [5] Crawford, M. (2010, May/June). Forward osmosis technology may revolutionize water reclamation in the oilfield.
- [6] U.S. Department of the Interior Bureau of Reclamation. Forward osmosis water purification. *Reclamation Managing Water in the West*.
- [7] Lutchmiah, K., Rietveld, L. (2010). Forward osmosis in sewer mining.
- [8] Abdalla, C.W., Drohan, J., Swistock, B., Boser, S. (2011). Penn State extension Marcellus Shale gas well drilling: regulations to protect water supplies in Pennsylvania. *Cooperative Extension College of Agricultural Sciences*.
- [9] Donovan, M. (2010). Method and apparatus for generating power utilizing forward osmosis. *United States Patent Application 20100212319*.
- [10] McCutcheon, J.R., McGinnis, R.L., Elimelech, M. (2005). A novel ammonia-carbon dioxide forward osmosis desalination process. *Desalination*, 174, 1-11.
- [11] McGinnis, R.L. (2002). Osmotic desalination process. *US Patent Pending PCT/US02/02740*.
- [12] McCutcheon, J.R., McGinnis, R.L., Elimelech, M. (2006). Desalination by a novel ammonia carbon dioxide forward osmosis process: influence of draw and feed solution concentrations on process performance. *Journal of Membrane Science*, 278, 114-123.
- [13] Hydration Technology Inc. (2005). HTI Military/X Pack from www.hydratationtech.com.
- [14] Hydration Technologies Inc. (2005). Hydration bags-technology overview from www.hydratationtech.com.

- [15] Engelman, R., Cincotta, R.P., Dye, B., Gardner-Outlaw, T., Wisniewski, J. (2000). People in the balance: population and natural resources at the turn of the millennium. *Population Action International, Washington, D.C.*
- [18] Loeb, S., van Hessen, F., Levi, J., Ventura, M. (1976). *11th Intersociety Energy Conversion Engineering Conference*. Nevada.
- [19] A. Seppala, M.J. Lampinen, W. Kotiaho, *Int. J. Energy Res.* 25 (2001) 1359.
- [20] Hickenbottom, K.L., Hancock, N.T., Hutchings, N.R., Appleton, E.W., Beaudry, E.G., Xu, P., Cath, T.Y. (2012). Forward osmosis treatment of drilling mud and fracturing wastewater from oil and gas operations. *Desalination*, doi: 10.1016/j.desal.2012.05.037.
- [21] Holloway, R.W., Childress, A.E., Dennett, K.E., Cath, T.Y. (2007). Forward osmosis for concentration of anaerobic digester centrate. *Water Research*, 41, 4005-4014.
- [22] CET Engineering Services. (2008). Borough of Middletown Water and Sewer System Annual Report. CET Engineering Services 1240 North Mountain Road Harrisburg, Pennsylvania.
- [23] Hancock, N.T., Xu, P., Roby, M.J., Gomez, J.D., Cath, T.Y. (2013). Towards direct potable reuse with forward osmosis: technical assessment of long-term process performance at the pilot scale. *Journal of Membrane Science*, 445, 34-46.
- [24] Zang, X., Yang, H., Wang, X., Fu, J., Xie, Y. F. (2013). Formation of disinfection by products: Effect of temperature and kinetic modeling. *Chemosphere*, 90, 634-639.
- [25] Cath, T.Y., Childress A.E., Elimelech M. (2006). Forward osmosis: principles, applications, and recent developments. *Journal of Membrane Science*, 281, 70-87.
- [26] Gray, G.T., McCutcheon, J.R., Elimelech, M. (2006). Internal concentration polarization in forward osmosis: role of membrane orientation. *Desalination*, 197, 1-8.
- [27] Braghetta, A., DiGiano, F., Nilson, J., Utne, B. (1994). Fouling of nanofiltration membranes by natural organic matter. *Critical Issues in Water and Wastewater Treatment*, pp 220228.
- [28] Mariñas, B.J., Selleck, R.E. (1992). Reverse osmosis treatment of multicomponent electrolyte solutions. *Journal of Membrane Science*, 72, 211-229.

- [29] Jacangelo, J.G., Trussell, R.R., Watson, M. (1997). Role of membrane technology in drinking water treatment in the United States, *Desalination*, 113, 119-127.
- [30] Braghetta, A., DiGiano, F., Ball, W. (1997). Nanofiltration of Natural Organic Matter: pH and Ionic Strength Effects. *Journal of Environmental Engineering*, 123(7), 628–641.
- [31] Hancock, N.T., Xu, P., Heil, D.M., Bellona, C., Cath, T.Y. (2011). Comprehensive bench- and pilot-scale investigation of trace organic compounds rejection by forward osmosis. *Environmental Science and Technology*, 45, 8483-8490.
- [32] Millat, A. (2011). Effect of ionic strength and salt type on humic acid fouling of forward osmosis membranes. Senior Honor Thesis Dissertation. Department of Mechanical Engineering, The Ohio State University, 2011.
- [33] Xie Y. F. (2003). *Disinfection Byproducts in Drinking Water: Formation, analysis, and control*. Lewis Publishers.
- [34] Scharlin, P. (1986). Application of acidity function method to the determination of pka values of trihalomethanes. *Acta Chem. Scand. A* 40: 207-209.
- [35] Slingsby, R., Saini, C., Pohl, C. Determination of Haloacetic Acids in Water Using IC-ESI MS/MS. Thermo Fisher Scientific, Sunnyvale, CA, USA.
- [36] DESWARE Encyclopedia of Desalination and Water Resources (2004-2013). Energy requirements of desalination process from <http://www.desware.net/desa4.aspx>.
- [37] Water Science and Technology Volume 33, Issues 10–11, 1996, Pages 1–14 Wastewater Reclamation and Reuse 1995 Wastewater reclamation, recycling and reuse: past, present, and future.
- [38] Water Reuse Potential for Expanding the Nation’s Water Supply through Reuse of Municipal Wastewater. National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001. <http://dels.nas.edu/resources/static-assets/materials-based-on-reports/reports-in-brief/Water-Reuse-Report-Brief-Final.pdf>.
- [39] MWH (2005). *Water treatment principles and design* (2nd ed.). Hoboken, NJ: John Wiley & Sons.

Appendix A

Synthetic Brackish Water Composition

Compound	Concentration (mg/L)
NaCl	9459
KCl	210
MgCl ₂	212
CaCl ₂	386
NaSO ₄	740
NaHCO ₃	2892
Na ₂ SiO ₃	240

Appendix B

UV₂₅₄ Absorbance: Continuous Data

Initial values

Treated Wastewater: 1.5

Filtered wastewater: 0.18 (0.45 μm Gelman ACRODISC Disposable Filter)

Brackish Water: 0.1

Time (min)	Temperature (°C)	Absorbance (cm ⁻¹)
0	23.6	0.215
2	23.6	0.2112
4	23.6	0.2048
6	23.6	0.2008
8	23.6	0.1998
10	23.6	0.1999
12	23.6	0.1996
14	23.6	0.1991
16	23.6	0.199

Time (min)	Temperature (°C)	Absorbance (cm⁻¹)
18	23.6	0.1995
20	23.6	0.1987
22	23.6	0.198
24	23.7	0.1973
26	23.7	0.1973
28	23.7	0.1969
30	23.7	0.1967
32	23.7	0.1962
34	23.7	0.1968
36	23.7	0.1961
38	23.7	0.1967
40	23.7	0.1964
42	23.7	0.1962
44	23.7	0.196
46	23.7	0.1955
48	23.7	0.1956
50	23.7	0.1955
52	23.7	0.1952

Time (min)	Temperature (°C)	Absorbance (cm⁻¹)
54	23.7	0.1959
56	23.7	0.1954
58	23.7	0.1957
60	23.7	0.196
62	23.7	0.1956
64	23.7	0.1961
66	23.8	0.1958
68	23.8	0.1963
70	23.8	0.1962
72	23.8	0.1964
74	23.8	0.1963
76	23.8	0.1967
78	23.8	0.1971
80	23.8	0.1971
82	23.8	0.1979
84	23.8	0.1977
86	23.8	0.1978
88	23.9	0.1983

Time (min)	Temperature (°C)	Absorbance (cm⁻¹)
90	23.9	0.1987
92	23.9	0.1984
94	23.9	0.1986
96	23.9	0.1988
98	23.9	0.1988
100	23.9	0.199
102	23.9	0.1996
104	23.9	0.1995
106	23.9	0.1997
108	23.9	0.1999
110	23.9	0.1998
112	23.9	0.1995
114	23.9	0.1997
116	23.9	0.2002
118	23.9	0.2001
120	24	0.2006
122	24	0.2005
124	24	0.2004

Time (min)	Temperature (°C)	Absorbance (cm⁻¹)
126	24	0.2003
128	24	0.2007
130	24	0.2008
132	24	0.2008
134	24	0.201
136	23.9	0.2012
138	23.9	0.2008
140	23.9	0.201
142	23.9	0.2014
144	23.9	0.2014
146	23.9	0.2013
148	23.9	0.2012
150	23.9	0.2016
152	23.9	0.2017
154	23.9	0.2017
156	23.9	0.2013
158	23.9	0.2018
160	23.9	0.2017

Time (min)	Temperature (°C)	Absorbance (cm⁻¹)
162	23.9	0.2018
164	23.9	0.202
166	23.9	0.202
168	23.9	0.2021
170	23.9	0.202
172	23.9	0.2021
174	23.9	0.2025
176	23.9	0.2024
178	23.8	0.2021
180	23.8	0.2027
182	23.8	0.2027
184	23.8	0.2027
186	23.8	0.2028
188	23.8	0.2029
190	23.8	0.2028
192	23.8	0.2034
194	23.8	0.203
196	23.8	0.2032

Time (min)	Temperature (°C)	Absorbance (cm⁻¹)
198	23.8	0.2027
200	23.8	0.2033
202	23.8	0.2038
204	23.8	0.2031
206	23.8	0.2032
208	23.8	0.2038
210	23.7	0.2039
212	23.7	0.2036
214	23.7	0.2039
216	23.7	0.2042
218	23.7	0.2042
220	23.7	0.2045
222	23.7	0.2045
224	23.7	0.2049
226	23.7	0.2046
228	23.7	0.2048
230	23.7	0.2049
232	23.7	0.2051

Time (min)	Temperature (°C)	Absorbance (cm⁻¹)
234	23.7	0.2051
236	23.7	0.2054
238	23.7	0.2053
240	23.7	0.2056
242	23.7	0.2058
244	23.7	0.2055
246	23.7	0.2058
248	23.7	0.2057
250	23.7	0.206
252	23.7	0.2061
254	23.7	0.2062
256	23.7	0.2064
258	23.7	0.2064
260	23.7	0.2065
262	23.7	0.2065
264	23.7	0.207
266	23.7	0.2067
268	23.7	0.2072

Time (min)	Temperature (°C)	Absorbance (cm⁻¹)
270	23.7	0.2073
272	23.7	0.2072
274	23.7	0.2077
276	23.7	0.2075
278	23.7	0.2074
280	23.7	0.2081
282	23.6	0.2079
284	23.6	0.208
286	23.6	0.2076
288	23.6	0.2079
290	23.6	0.2084
292	23.6	0.2079
294	23.6	0.2085
296	23.6	0.2085
298	23.6	0.2085
300	23.6	0.2086
302	23.6	0.2084
304	23.6	0.2086

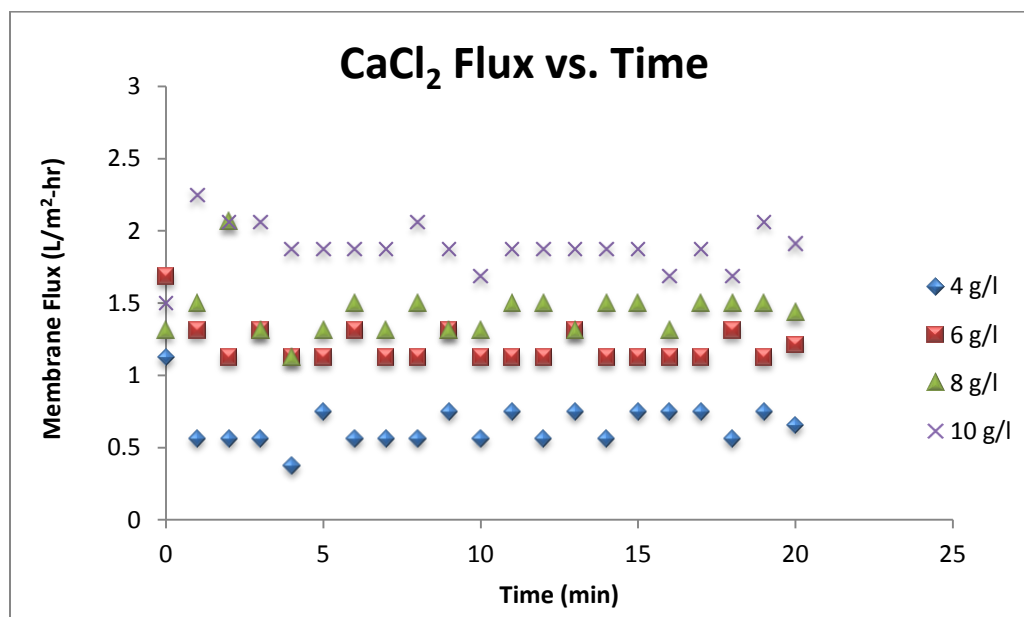
Time (min)	Temperature (°C)	Absorbance (cm⁻¹)
306	23.6	0.2088
308	23.6	0.2092
310	23.6	0.209
312	23.6	0.209
314	23.6	0.2092
316	23.6	0.2096
318	23.6	0.2093
320	23.6	0.2094
322	23.6	0.2093
324	23.6	0.2094
326	23.6	0.2095
328	23.6	0.2096
330	23.6	0.2098
332	23.6	0.2097
334	23.6	0.2098
336	23.6	0.2099
338	23.6	0.21
340	23.6	0.2101

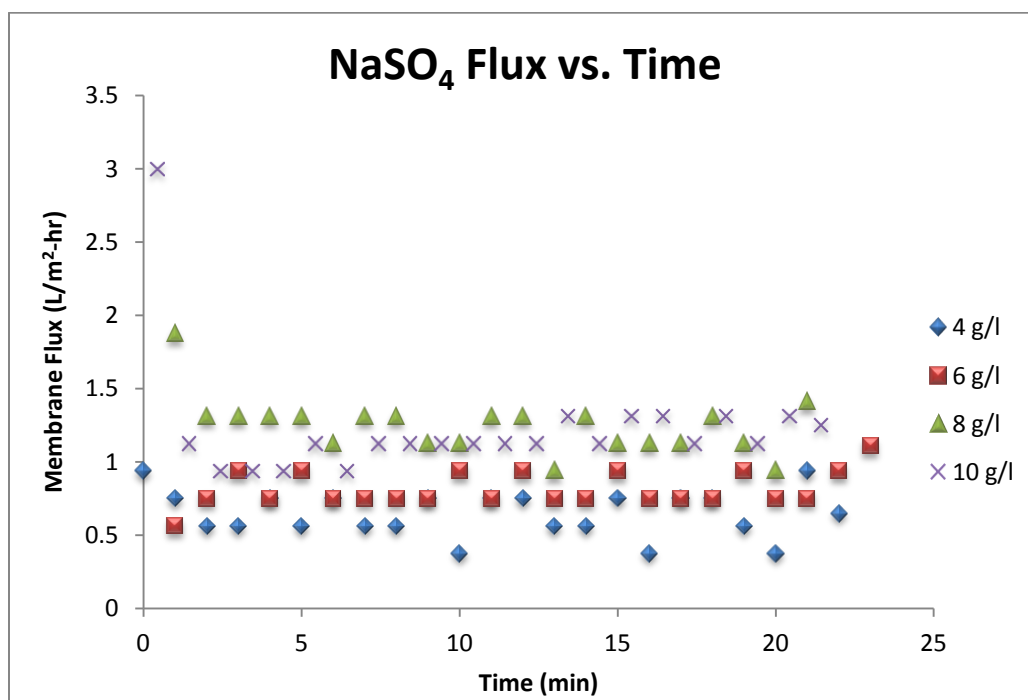
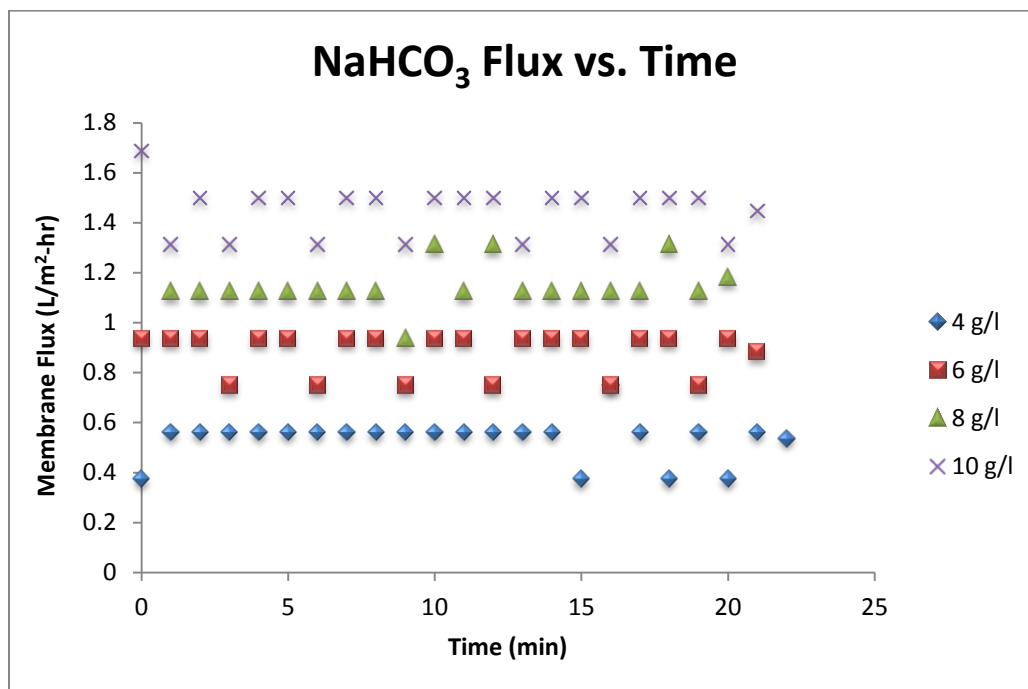
Time (min)	Temperature (°C)	Absorbance (cm⁻¹)
342	23.6	0.2101
344	23.6	0.2102
346	23.6	0.2104
348	23.6	0.2105
350	23.6	0.2105
352	23.6	0.2106
354	23.6	0.2111

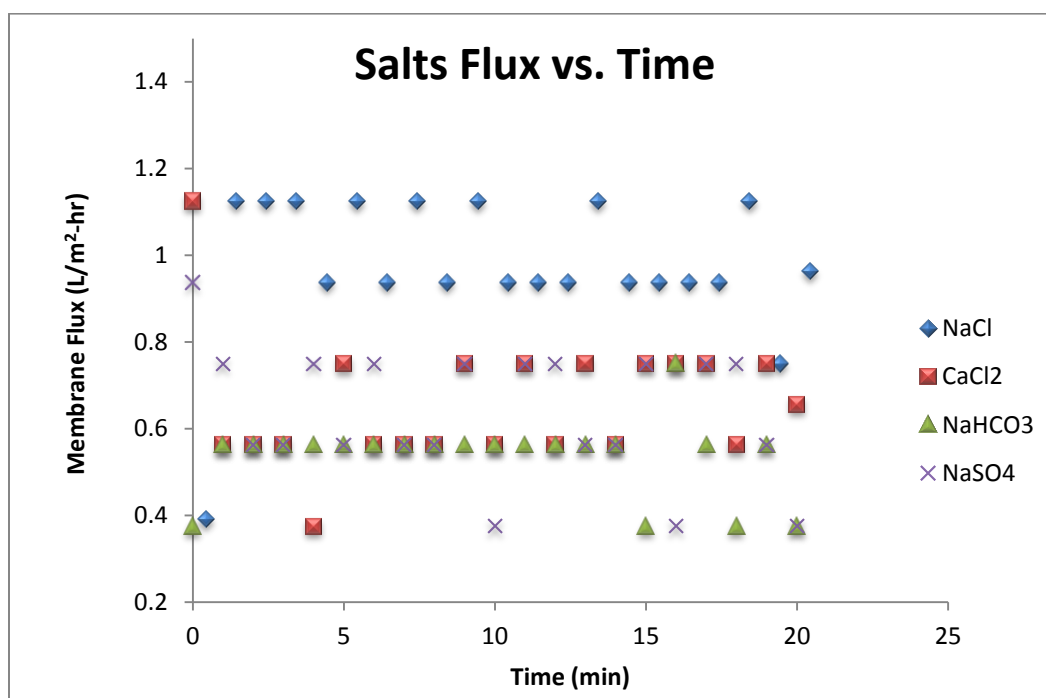
Appendix C

Effect of salt type and concentration on the membrane flux

Compound	Concentration (g/L)			
NaCl	10	8	6	4
CaCl ₂				
NaSO ₄				
NaHCO ₃				







Appendix D

$$\Pi = iMRT$$

i = van't Hoff dissociation factor

M=molality

R=gas constant

T=absolute temperature

Initial concentration = 10 g/L (each compound)

Compound	Dissociation Factor (i)	Molality [mol/L]	Osmotic Pressure (π)
NaCl	2	0.17	0.34
NaHCO ₃	2	0.090	0.24
CaCl ₂	3	0.12	0.27
Na ₂ SO ₄	3	0.070	0.21