QATAR UNIVERSITY

College of Engineering

TREATMENT OF DEWATERING CONSTRUCTION WATER USING AN INTEGRATED FORWARD OSMOSIS SYSTEM

By

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ABSTRACT

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Master of Science in Environmental Engineering

Title: Treatment of Dewatering Construction Water Using an Integrated Forward Osmosis System

Supervisor of thesis: Alaa Hamdan Al-Hawari

Forward osmosis (FO) has gained substantial research attention in recent years as a new emerging water treatment technology with low energy consumption. In this study, forward osmosis has been used to treat dewatering construction water (DCW). The impact of flow rates of feed solution (FS) and draw solution (DS), the placement of a spacer on the support layer of the FO membrane and the pretreatment of the feed solution on the performance of the forward osmosis process were investigated. It was found that a feed solution and draw solution flow rate of 2.9 LPM gave the highest membrane flux with an initial value of 0.055 L/m^2.min compared to 0.048 L/m^2.min, 0.048 L/m^2.min and 0.044 L/m^2.min at the flow rates of 2.2 LPM, 1.5 LPM and 0.8 LPM, respectively. The highest recovery rate of 24% was obtained at a flow rate of 2.2 LPM compared to a recovery rate of 16%, 21% and 15% for flow rates of 2.9 LPM, 1.5 LPM and 0.8 LPM, respectively. The influence of pretreating DCW on the performance of the FO process was also investigated. Pretreatment by primary settling and multimedia filtration were

carried out. Results showed that the recovery rate of the FO process increased the most after pretreatment by multimedia filtration with a recovery rate of 30% compared to 22% and 15% for pretreatment by settling and without treatment, respectively. Furthermore, it was found that when the membrane’s active layer was facing the draw solution in (DS-AL) operation mode, a better membrane flux was achieved when compared to the membrane’s active layer facing the feed solution (FS-AL).

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DEDICATION

I would like to dedicate my dissertation work to my beloved family for their untiring support and sacrifices. I send my gratitude, specifically, to my loving parents, wife and adorable son whose presence has added indescribable happiness and motivation to my life.   This work would have never been completed without the encouragement of my professors. I humbly dedicate the paper to you for your guidance.

Thank you for all that you have been, I appreciate your existence in my life.

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CHAPTER1: INTRODUCTION

1.1 Water Issues

1.1.1Overview of Water Resources

Water shortage is a fundamental issue increasing in magnitude and urgency around the globe. The severity of this shortage is being escalated as a consequence of the world's huge population growth of almost 1 billion people per decade [1]. In response to the shortage in fresh water supplies, water resources management has been highlighted. Accordingly, efforts were made in the direction of searching for freshwater alternatives aiming to withstand the rapid increase in demand. Over decades of research in this area, two promising technologies were identified: desalination of sea water and reclamation of wastewater. In arid and semi-arid regions like the Arabian Gulf a great challenge is posed. While water needs will continue to increase, natural fresh water resources are very limited. As the problem is predominant, looking into the alternatives is essential. Desalination of sea water has been considered as an additional fresh water source. Great efforts have been made in developing desalination as an efficient alternative for fresh water. However, desalination has always been regarded as a high-energy consumption process that counts for the very high costs associated to it [2]. Other efforts have been directed towards wastewater reclamation. Usually, wastewater undergoes secondary treatment before being discharged to the nearest water source. Advanced treatment of the secondary effluent can bring the water quality up to high standards so that it can be reused in several applications. The reuse of treated wastewater evolved as a solution to the conflict of limited water resources with increasing water demand. Moreover, treated wastewater is a renewable water resource that increases along with the increase in water consumption. The importance of wastewater reclamation in the field of water resources development and management is currently highly acknowledged [3]. One of the basic considerations when planning for wastewater treatment is to clearly identify the targeted reuse application of the water. The reuse application governs the type of wastewater treatment needed and the degree of reliability required for the treatment process [4]. Globally, applications of irrigation and agricultural landscape currently represent the largest use of reclaimed wastewater. In the Arabian Gulf region, proposals for the use of reclaimed water over the last two decades have focused on the utilization of this water in landscape irrigation and for groundwater recharge [5].

1.1.2 Water Resources in the State of Qatar

In Qatar, water scarcity is one of the vital environmental issues. The level of rainfall in Qatar is considered as one of the lowest in the world. Accordingly, the country mainly depends on desalination of sea water, ground water and water recycling to meet the increasing demand of a population that reached 1.7 million in mid-2010. Considering that desalination, which accounts for 50% of water use, is currently the sole source on which Qatar depends on to provide the domestic and industrial water supplies, the high per capita use has caused the water stress to rise even higher. Ground water from aquifers which accounts for 36% of the water use in Qatar, is entirely used in agriculture. The recycled water from wastewater treatment plants accounting for 14% of the water use in Qatar, is predominantly used for irrigation purposes (Figure 1). As for industrial wastewater, in the past industrial facilities in Qatar were allowed to discharge the treated wastewater directly to the sea if it met the local environmental regulations for discharge. However, in 2009, the Ministry of Environment started heading towards the goal of "zero discharge", a principle by which all industrial wastewater has to be completely recycled. This means that wastewater has to be treated and re-used again in the process and should not be released into surface water. The industrial facilities are currently working on timed plans that will allow them to comply with the "zero discharge" goal. The challenge imposed is to be able to come up with engineering solutions that would help in upgrading the existing wastewater treatment facilities. This would enable the production of high quality effluent that can be reused in different applications such as injection in deep aquifers, irrigation and re-implementation of the treated water in the process for cooling and backwashing purposes [6].

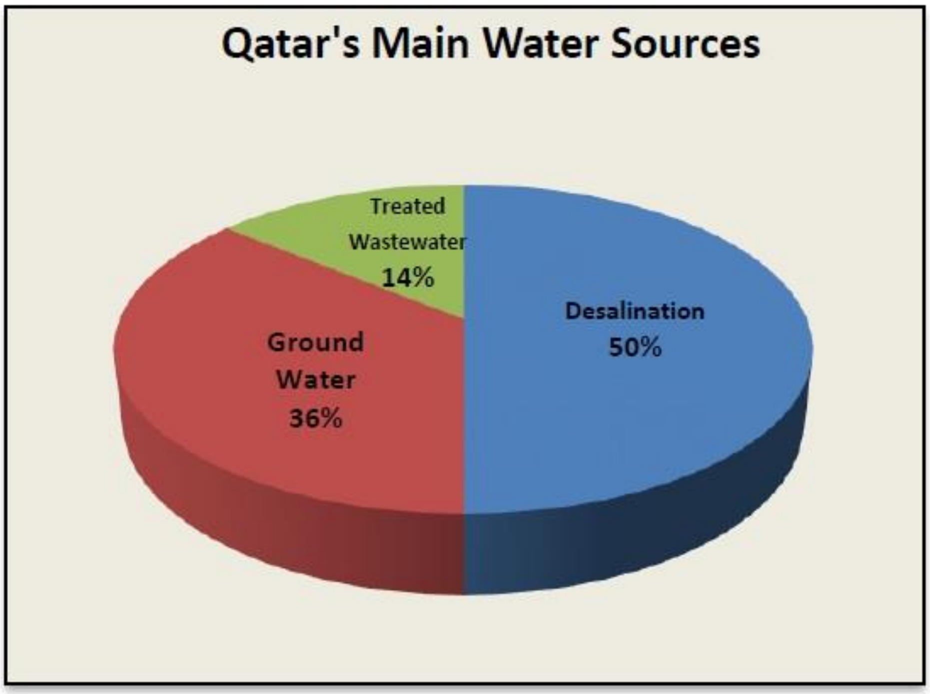

Figure 1: Main sources of water used in Qatar. Adopted from [6]

1.2 Wastewater Treatment

1.2.1 Wastewater Treatment Overview

Wastewater treatment plants are classified under two basic titles: biological and physical/chemical plants [7]. Biological processes are usually used to treat domestic and industrial wastewater due to their biodegradable contents [8] [9]. Fundamentally, they use the same natural biodegradation processes that would occur in the receiving water. However, the reactions take place under controlled conditions [10]. Physical/chemical plants are also used for both municipal and industrial wastewater but they are mainly used in industrial wastewater treatment [11]. Industrial wastewater often contains non-biodegradable pollutants which cannot be processed by the microorganisms [11] [12]. Depending on the industry itself some industries deal with biodegradable materials such as food, textile, paper and plastic industries. Biological treatments are applied in such industries in addition to other physical/chemical treatment units [13] [14] [15]. The physical processes could be simply settling tanks or they could be mechanically aided. For example, this could be done by providing gentle stirring to the water suspension to cause small particles to collide with each other to form larger particles which will settle faster [16]. When wastewater treatment was first implemented, the target for municipal wastewater was to merely decrease the oxygen demand, colloidal particles, dissolved inorganic compounds and detrimental constituents. Over the years, however, the target was to treat the wastewater to higher standards. This imposes that the water has to go through different stages of treatment to produce high quality effluent. For municipal wastewater, the treatment consists of primary, secondary and tertiary treatment stages. The primary treatment is the very early stage including screening and sedimentation mainly aiming to remove the huge particulates from the water stream [17]. The secondary treatment, which is considered as the core of the treatment process, involves the biological process conducted through aeration tanks [18]. The tertiary or advanced treatment is the polishing stage in which advanced methods such as membrane processes or multi-media filtration are employed [19]. The general scheme of any wastewater water treatment plant is shown in Figure 2. Primary and secondary treatment stages can achieve the removal of BOD and colloidal particles contained in a wastewater stream [17]. However, the level of removal is not up to the targeted standards for water discharge to natural water sources nor for waste reuse applications [20].

The quality of effluent of the secondary treatment in most of the cases has proved to be of insufficient quality to be pumped back into receiving waters or to be reused and recycled in the industry itself. Hence, further treatment steps were added to wastewater treatment plants to provide efficient removal of undesired water constituents [17] [20]. Therefore, in response to the need to improve secondary effluent quality, advanced wastewater technologies were brought into the scheme of wastewater treatment plants [21]. Advanced wastewater treatment processes would produce a high quality effluent that could be recycled and reused in municipal or industrial usages [17] [19].

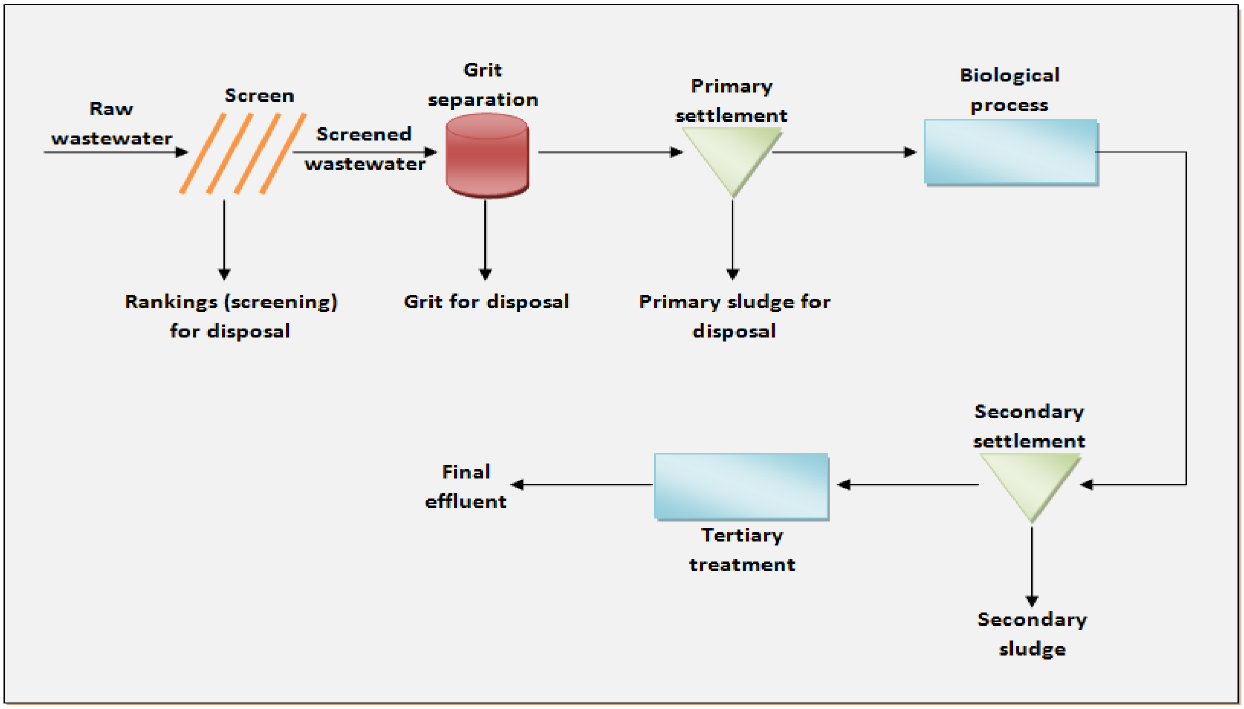

Figure 2: General wastewater treatment plant scheme. Adopted from [22]

1.2.2 Wastewater Definition and Types

Wastewater is defined as water that carries wastes from municipal or industrial institutions, or mixed with ground water, surface water and/or storm water. Wastewater contains high levels of organic pollutants, pathogens, and inorganic pollutants [23]. Some types of wastewater also contain toxic compounds especially when they are generated from industrial sources [24] [25]. Wastewater is classified into four main categories based on the source: domestic wastewater, industrial wastewater, storm water and infiltration and inflow water. Domestic wastewater is that discharged from residences and commercial institutions [12]. Industrial wastewater is the wastewater discharge from industrial plants carrying industrial wastes [24]. Domestic and industrial wastewater are considered of higher importance among the four categories due to their huge quantities. Storm water is the water which results when flooding occurs after heavy rainfall [26]. Finally, Infiltration or inflow water is defined as the water entering the sewer system through direct or indirect means such as porous and cracked walls of pipes or leaking joints. Inflow water is the storm water penetrating into the sewer system [17].

1.3 Dewatering Construction Water

Dewatering and construction dewatering are expressions used to define the removing of groundwater or surface water from the construction area. Usually, the process of dewatering occurs before footings excavation by either pumping or evaporation the low water table, which could lead to problems occurring during excavations. Dewatering could also indicate the process of removing water by wet classification from soil. In order to protect the quality of surface waters (e.g., lake, streams, rivers, etc.), specific conditions of government clean water acts and related federal and state regulations should be adhered to, by offering activities that help to discharge pollutants in an environmentally friendly practice.

Potential contaminants contain, but are not limited to the following, petroleum hydrocarbons, total suspended solids/sediment, metals, organics and high or low pH based soil and groundwater characteristics. Hence, the activities of dewatering undergo authorizations by permit and compliance with permit authorities.

1.3.1 Dewatering Construction Water Extraction Techniques

The option of dewatering procedure would depend mostly on the type of soil and permeability as well as the amount of groundwater to be taken off. It is restricted in its application, the most effective method of dewatering that aims to reduce the environmental harm, meet most legal limits, and make sure ensure the protection of personnel on-site. The simplest form of the system of dewatering within a construction site is the Sump Pit method. Usually Sump Pit is considered as simplest, fastest and least expensive solution. As shown in Figure3, it can be utilized at the beginning of construction as the excavating phase commences. Sump Pits are effective when considering groundwater filtering. Unless, the groundwater has touched silt or/and limestone as this would result into noticeable high turbidity. If the soil contains silty characteristics, it is recommended to install aggregates and geotextile in the sump pit for improving the dewatering effluent quality and reducing the turbidity significantly [27].

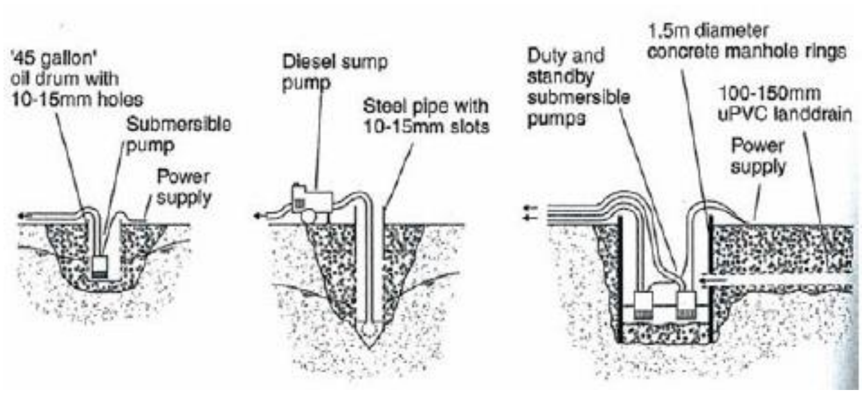

Figure 3: Typical Sump Pits, a) Perforated oil drum, b) Perforated steel pipe with driving point, c) Concrete manhole rings fed by French drains. Adopted from [28]

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One of the most common practices of dewatering construction water extraction is the well-system as shown in Figure 4. In this extraction technique, wells will be drilled surrounding the construction location and duty and standby pumps will be installed into these wells. This practice is best-known for projects that need deep excavation for basements due to its effectiveness in sandy soil, flexibility, easiness of installation and relative low cost [27].

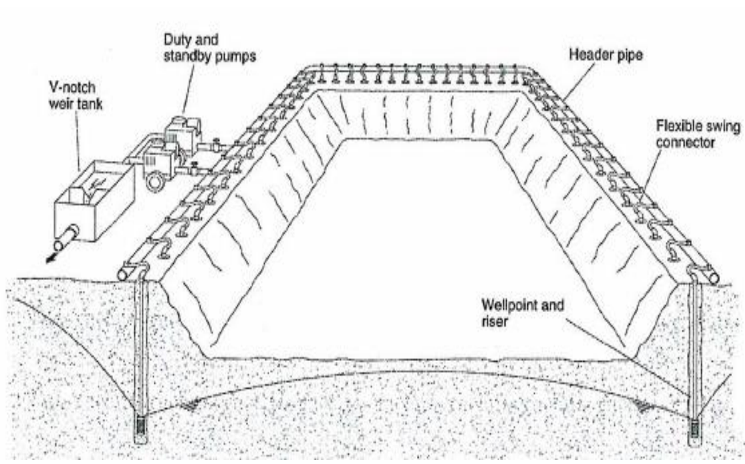

Figure 4: Components of well point system. Adopted from [28]

As shown in Figure 5, deep wells are usually processed using a control cabin, and are installed with the filter pack as well as submerging pumps. Although its installation is expensive, it has the advantage of needing fewer wells than the well system with higher efficiency. However, these type of wells are rarely used in Qatar [27].

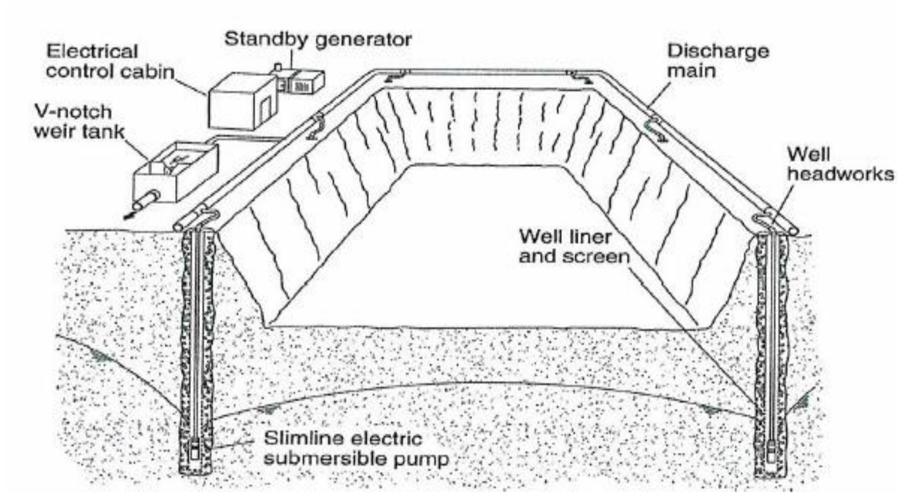

Figure 5: Components of deep well system. Adopted from [28]

French drains as shown in Figure 6, are widely used and commonly known as trenches within Qatar's construction projects, especially for infrastructure projects. What makes French drains popular is the fact that it is effective in monitoring groundwater after concrete foundations casting and has the ability to control shallow groundwater with a relatively low-cost. Trenches are established to allow groundwater to flow to the surface, then perforated pipes are used to collect the groundwater to be treated using filtration [27].

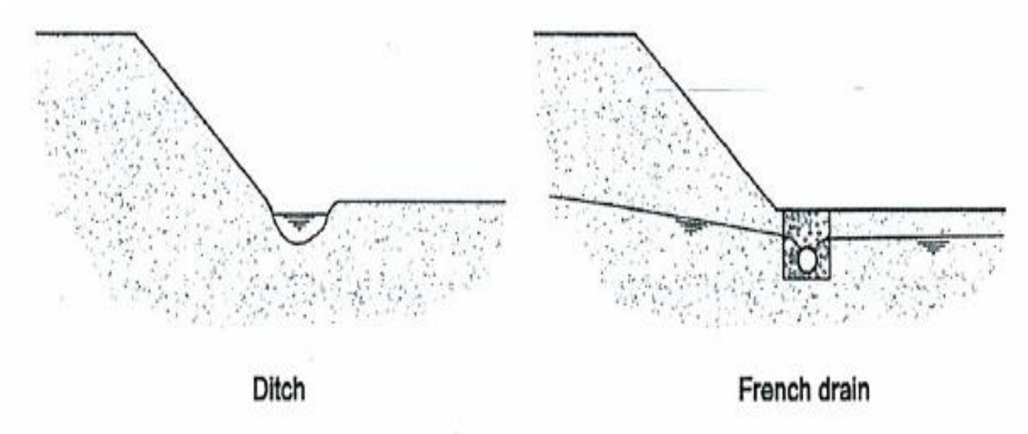

Figure 6: Ditch and french drain. Adopted from [28]

1.3.2 Dewatering Construction Water Treatment

The most effective and widely used method of dewatering construction water treatment in Qatar projects is the sedimentation tank. The tank is used, at first, in order to maximize the travelling distance of the effluent prior to reaching the point of discharge, hence, raising the efficiency of settlement. Most of Qatar's projects tend to provide a settlement tank, specifically the ones that apply for a discharge permit. The type of soil, flow rate estimation and retention time of suspended solids are the major factors that must be considered when choosing the settlement tank [27].

For silt and fine grained suspended particles removal, the dewatering tank and gravity bag filter, which are not expensive, could be applied to the treatment of DWC. Initially, a fabric filter would be added to the dewatering tank in order to remove sediments such as: silt, sand and visible oil. The flow will move through the filter to remove sediments before being deposited at tank's bottom. This type of tank must be cleaned periodically based on the inspection and flow reduction. Secondly, for the gravity bag filter, which is widely known as a dewatered bag and is made from a geotextile texture that filters out the sediments contained in the dewatering water. This bag filter is a disposable filter and it does not require periodic cleaning. Once solids have passed through the filter or water blockage, the filter should be replaced. Ease of installation, low cost and efficiency of sediments removal make the gravity bag filter widely used on construction sites [27].

1.3.3 Disposal of Dewatering Construction Water

Dewatering effluent will be disposed of by several disposal methods such as: discharge to sea through the network of surface and groundwater, direct discharge to the sea, discharge to lagoon covered by geotextile and discharge using deep well injection. Disposal of dewatering effluent to the sea through the network of surface and groundwater is the widespread method in Qatar. These networks eventually go to outfalls that would be released to the sea. Based on surface and groundwater network availability in the construction site, the disposal method to the network would be selected either via pipelines or tankers. Moreover, a secondary treatment method should be applied to achieve dewatering effluent settlement before being discharged to the outfall point [27].

The quantity of dewatering effluent, detailed engineering drawing of the proposed lagoon and the duration of effluent discharge are the main criteria that should be satisfied to have better disposal method with minimum negative impact on the lagoon.

Furthermore, discharge using deep well injection is a common disposal practice in Qatar for the sewage effluent from wastewater treatment plant with a minimum depth of 400 – 600 m depth of the well. Yet, using well injection for dewatering effluent is limited to only a few major projects [27].

1.4 Objectives and Scope of Work

In this study dewatering construction water was used as a feed solution in forward osmosis in order to dilute seawater for further treatment. According to the literature the quality of DCW is deemed to be a promising feed solution due to its low salinity. The impact of different parameters on the FO process was studied, namely, the flow rates of feed and draw solutions, orientation of membrane and the placement of spacer. In addition, the impact of a pretreatment process for the feed solution was studied. Two pretreatment process were performed: sedimentation and multimedia filtration. The following parameters were studied:

FO process

- Flow rate of feed and draw solution (0.8, 1.5, 2.2, 2.9) LPM
- Impact of the existence of a spacer on the membrane's support layer
- Orientation of the membrane (DS-AL) and (FS-AL)

Pretreatment

- Settling
- Multimedia filtration

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

2.1 Desalination

Due to the current population inflation the need of water has become more vital. Hence, research committees put the effort in the direction of investigating new water treatment technologies with low energy consumption, inexpensive cost and lower negative environmental effects. Wastewater reclamation, sea and brackish water desalination are the main solution to resolve scarcity of fresh water.

Desalination is the process of producing high quality potable water for daily consumption by separating dissolved salt and minerals from sea water. The process of desalination started when the salt was the targeted product, where it could be applied to municipal, industrial and commercial wastewater. Ancient Greek used a procedure of evaporation for fresh water by boiling salty water. Moreover, Romans used clay filtration to remove salt [29]. The first to build a desalination machine back in 1852 was Britain. The plant was built in Saudi Arabia in 1938 [29]. In early 1970s the concept of desalination became applicable for different industries [30]. Meanwhile, in this period the first major RO plant was built in Florida [31]. Subsequently, many improvements have been applied to desalination technology to increase the efficiency and minimize the operation cost. Desalination technologies are classified into two major categories:

Thermal desalination technologies that depend on changing water physical properties. For example: Multi-Stage Flash Distillation (MSF), Multi-Effect Distillation (MED) and Vapor Compression Distillation (VCD). And membrane desalination technology that utilizes the membrane to induce salt separation from impaired water. Such as: Reverse Osmosis (RO), Forward Osmosis (FO),Electrodialysis (ED) and Membrane Distillation (MD).

An extensive amount of energy is consumed to operate desalination plants in both types, and the source of energy is nonrenewable such as fossil fuel that leads to greenhouse gases concentration and an increase in the effect of global warming [32] [33]. Despite the fact that desalination process is considered as an effective way to produce potable water, especially in GCC, yet environmental issues have raised due to increasing way toward desalination. The main concerns associated with desalination process are: Ecological effects linked initially with the intakes of seawater, environmental effects related brine discharge and greenhouse gases emissions because of fossil fuels burning from power plant and water desalination process. Greenhouse gases are mainly the gases that tend to trap heat in the atmosphere which will lead to global warming. Types of gases include CO_2, CH_4, N_2O, and fluorinated gases as HFCs, PFCs and SF6. At upper atmosphere a fine balanced quantity of these gases exists, in which it keeps the energy balance transfer among the atmosphere, land as well as space. Within current industry growth, the greenhouse gases emission increased and led to variance in both global and local climates [34] [35]. While making decisions about water treatment technologies besides subsequent water management system the energy will be the driving factor [36]. Therefore, attention about the associated environmental effects would be considered to reduce the negative impact by adopting environmentally friendly strategies with high efficiency, low cost and minimum environmental footprint [37].

2.1.1 Thermal Desalination Technologies

In this technology, the feed water will be heated to reach vapor phase and then condensation will take place and water will be collected as fresh water. The process will occur within a temperature ranging from 90-110C in MSF distillation, while in MED thermal distillation the temperature would be of 65-70C. Among the advantages of thermal distillation is the process of producing high water [38]. The total dissolved solid for both MSF and MED will be less than 50 ppm for produced distilled water [39]. However, some disadvantages could limit the efficiency of thermal distillation, as its processes need high temperature to heat the natural water, the occurrence of inorganic scaling would be considered as a major obstacle of the thermal processes. Notwithstanding the maximum efficiency would be achieved with elevating operating temperature by increasing the salt separation with peak overall flux, some limitations should be deemed due to the accumulation of salts such as: calcium carbonate and magnesium hydroxide [40].

2.1.2 Membrane Desalination Technologies

Nowadays, membrane technologies were improved noticeably to enhance the quality of treated water before being discharged to the environment. Membrane's modular nature, large and small scale application, ability to control the quality of produced water, minimum environmental negative impact, low cost of operation and low energy consumption are the main advantages of this technology that is gaining a substantial attention nowadays from research centers [41].

2.1.2.1Reverse Osmosis (RO)

Reverse osmosis or hyperfilteration is an essential emerging technology used since the development of semipermeable membranes. This technology is used to produce fresh potable water by separating dissolved salts and minerals from impaired water by enforcing a hydraulic pressure which is higher than feed solution osmotic pressure to drive the flow through the used semipermeable membrane from a higher concentration solution to the lower concentration solution [42]. The significance of osmosis, equilibrium and reverse osmosis is illustrated in Figure 7.

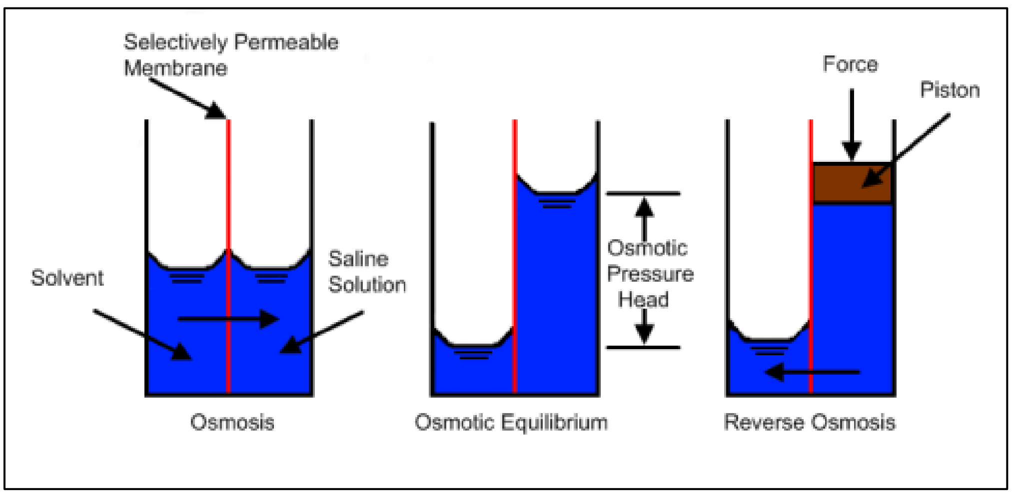

Figure 7: The significance of reverse osmosis. Adopted from [43]

One of the major components of RO system is the membrane used which is synthesized from different materials such as: polyamide, nylon, cellulose and polyether [42]. In Reid study that was carried out in late 1950s where the used membrane in this study was casted from cellulose acetate. However, the obtained flux from this work was minimum and not considered to be practical [44]. After Loeb and Sourirajan experiments in early 1960s, RO processes became more realistic where the membrane used in this study was synthesizing asymmetric cellulose acetate membranes that results in high water fluxes and slat rejection [45] [46]. After the enhancements that have been developed in cellulose acetate (CA) membranes the cellulose tri-acetate (CTA) membranes was synthesized. However, hydrolysis will occur in CA membrane due to high alkalinity or acidity of the feed solution which leads to narrow operation range of pH [47]. Polyamide thin film composite (TFC) membranes have many advantages over (CA) membranes from the point view of permeable flux and rejection of salt. Moreover, TFC membranes have wide operation range of pH, temperature, and to high resistance to chemicals. Based on the RO membranes advantages, it has become widely used in water treatment application for instance: industry reclamation of wastewater, ultrapure water production for industrial uses, desalination of seawater and brackish water [48]. In last decades, RO membranes have reached to a wide popularity based on the advancement of mechanical, biological and chemical strength that was enhanced better productivity membranes with reasonable salt rejection, better permeable flux and high fouling resistance. Based on these advantages, RO surpasses other desalination technologies and became widely used all over the world [49]. The cost of RO desalination has been reduced significantly from the start of RO commercialization [50]. For example, the required energy for desalination processes by RO system was 5-10 kWh/m3 which is now with the witnessed improvements of RO technologies turned to be 3 kWh/m3 [51]. However, the efficiency of RO from the side of energy consumption could not improve more than the current stage. Thus, only minor further enhancements could be applied [52]. And the other major membrane desalination process is forward osmosis (FO) and this technology considered to be low energy water treatment process to extract water with a high-quality from wastewater. Moreover, FO has no hydraulic pressure with minimum membrane fouling tendency. Based on these considerations, FO is deemed to be a cost-effective alternative in water treatment. Further explanations about FO will be carried out in the next section 2.3.

2.3 Forward Osmosis (FO)

Recently, forward osmosis was given substantial attention by researchers as an economical emerging reclamation technology with low energy consumption. The osmotic pressure difference will be the driving force of this technology. Where the flow will move from low concentration feed solution with low osmotic pressure across the semipermeable membrane toward high concentration draw solution with high osmotic pressure [53]. Contrasted with reverse osmosis (RO), where the applied hydraulic pressure is the driving force for these processes. However, FO processes have progressed to be operated commercially with minimum energy and most probably this energy will be consumed to operate both feed and draw solution pump. The concept of equilibrium osmotic state, forward osmosis (FO) and pressure retarded osmosis (PRO) is depicted in Figure 8.

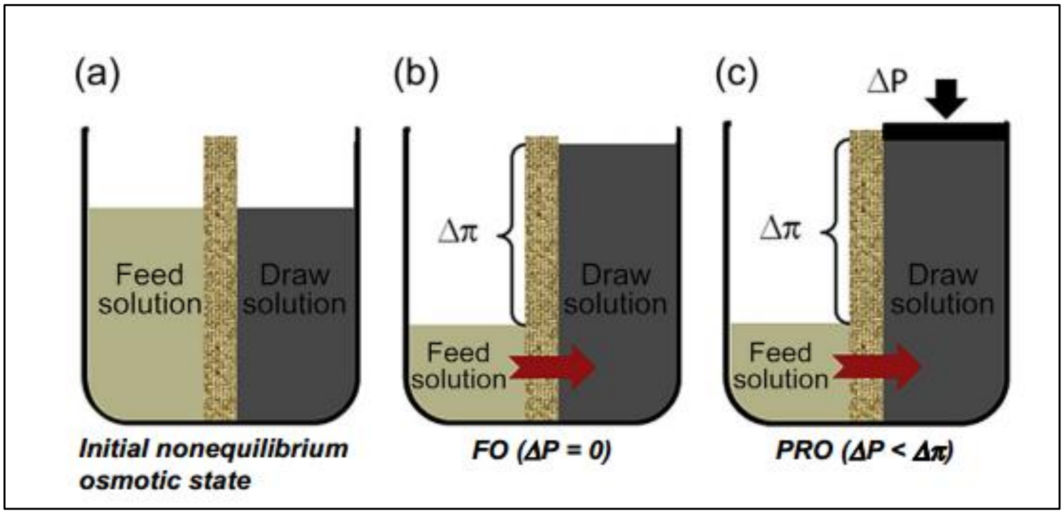

Figure 8: (a) Initial non-equilibrium osmotic state; (b) FO process in which no pressure is applied on the draw solution; (c) PRO process in which a hydrostatic pressure lower than the transmembrane osmotic pressure is applied on the draw solution. Adopted form [53]

It could be seen from figure 8, that the difference of draw solution and feed solution osmotic pressure ($\Delta\pi$) is the driven force in FO process. Moreover, if the hypothesized hydraulic pressure is applied to the DS side, the permeate flux will stop moving in the direction of DS and a state of equilibrium between DS and FS will be reached. Though, PRO is a closely similar to FO process in which the flow will be toward the draw solution. However, a hydraulic pressure that is less than the net osmotic pressure is applied in the draw solution side [54].

The osmotic pressure (π) for any diluted solution is given by Van't Hoff equation [55]:

$$\pi = MRT \tag{2.1}$$

Where M is the molar concentration of the solution, R is the universal gas constant (R=0.0821 L.atm.mol-1.K-1), and T is the absolute temperature measured in Kelvin. In the case of solute with strong electrolyte and completely dissociate in water having m ions, the Van't Hoff equation became [56].

$$\pi = \frac{mx_1RT}{V_2} \tag{2.2}$$

Where x_1 is the mole fraction of species 1 (electrolyte) and V_2 is the molar volume of water.

However, when solutions have high concentrations where the electrostatic interactions between the ions increase (non-ideal solution), Van't Hoff equation in not applicable in this case since it only describe and applicable to ideal and dilute solutions where ions behave independently of one another [48].

According to statistical thermodynamics theory, the osmotic pressure could be given as a function of the solute number density in the form of viral expansion [56]:

$$\frac{\pi}{ckT} = 1 + Bc + Cc^2 + Dc^3 + \cdots \tag{2.3}$$

Where k is Boltzmann's constant, B, C and D are the osmotic viral coefficients which are functions of temperature and chemical potential of the species in the salt solution [48] [57] and c is the solute number density given by the following equation [56] [58]:

$$c = N_A M \tag{2.4}$$

Where N_A is Avogadro's number and M is the molar concentration of the solute. For simplicity, OLI Stream software could be used to estimate the osmotic pressure of solution.

Water transport in FO, PRO, and RO described by the following equation [59]:

$$J_w = A(\sigma\Delta\pi - \Delta P) \tag{2.5}$$

Where J_w is the water flux, A is the water permeability coefficient of the membrane, σ is the reflection coefficient, Δπ is the difference of osmotic pressure across the membrane, and ΔP is the difference of applied hydraulic pressure.

From the above equation, FO, RO, and PRO depend on the following conditions:

- If $\Delta P > \Delta\pi$ then the process will be RO
- If $\Delta P = 0$ then the process is FO
- And if $\Delta\pi > \Delta P$ the system is functioning as PRO

In FO there is no hydraulic pressure applied and the difference of osmotic pressure between DS and FS is the driven force, then the equation can be expressed as:

$$J_w = A\sigma\Delta\pi_{Bulk} = A\sigma(\pi_{Draw,b} - \pi_{Feed,b}) \tag{2.6}$$

Where $\pi_{Draw,b}$ and $\pi_{Feed,b}$ is the draw and the feed solutions osmotic pressure, respectively. The assumption in equation 2.6 is based on no water flux will occur from the draw solution through FO membrane [60].

The following equation has been developed by Loeb et al.is to predict permeate flux in FO system. The assumption for their study is that the driving force in the system is mainly due to the difference between bulk osmotic pressure of DS and FS as shown in Figure 9 [61].

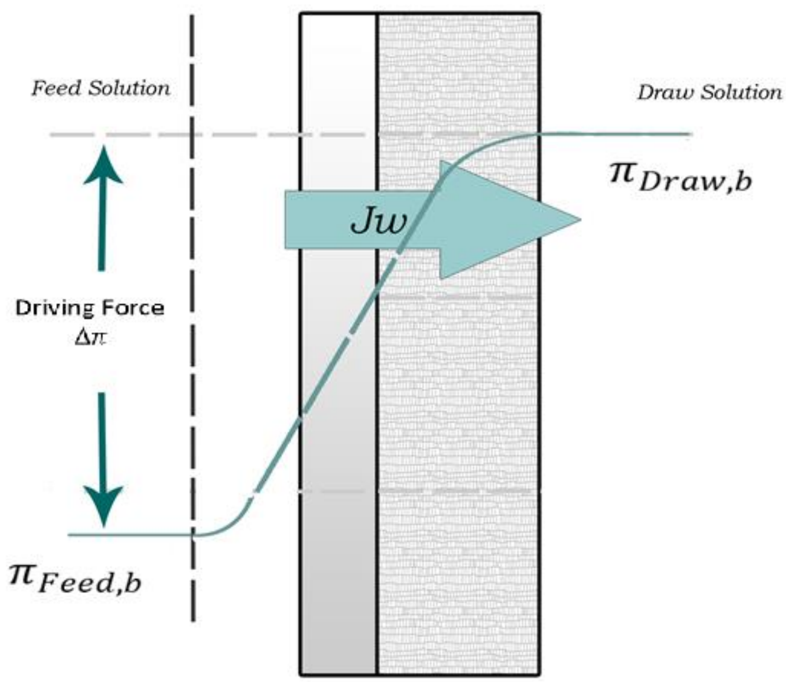

Figure 9: Symmetric membrane ideal driving force

In this study, the researchers have developed an equation that is applicable only when water flux has a relatively low value:

$$J_w = \frac{1}{K} ln\left(\frac{\pi_{Draw}}{\pi_{Feed}}\right) \quad (2.7)$$

Where K the solute diffusion resistance within membrane support layer, π_{Draw} and π_{Feed} is draw solution and feed solution osmotic pressure, respectively. Values for K can be obtained from the following equation:

$$K = \frac{t\tau}{\varepsilon D} = \frac{S}{D} \quad (2.8)$$

Where, t is membrane thickness, τ is tortuosity, ε is the membrane porosity, D is solute diffusion coefficient, and S is the structure parameter of the membrane.

It could be concluded that FO is operating under low or no hydraulic pressure. FO filtration processes take place under net osmotic pressure with minimum energy requirements compared to other desalination technologies [59] [45] [62]. Furthermore, membrane fouling which is major drawback associated with hydraulic pressure in RO has minimum impact on FO system and could be physically reversible [46] [62] [63].

2.3.1 Selection of Draw Solution

Choosing an ideal draw solution is a crucial factor that significantly influences the performance of FO technology. A suitable draw solution saves cost in addition to the fact that it promotes efficiency of the FO process. In order to utilize the afore-mentioned benefits the selected draw solution should fulfill several requirements for instance low toxicity and cost. In addition, to be able to produce high osmotic pressure and flexibility of diluted draw solution regeneration. An effort was made on the process of exploration of an appropriate draw solution for FO processes over the two couple of decades. Different compounds were illustrated in several researches. An overview of draw solutions, physicochemical properties, drawbacks and water flux was investigated in previous studies. Su et al. [64] has conducted an experimental study in order to reduce ICP and membrane fouling. In which, CA hollow fiber membrane obtained a water flux of 17.1 LMP with $MgCl_2$ draw solution. While water flux of 12.9 LMP was achieved with sucrose draw solution. After using sucrose as draw solution it was shown that it produced relatively low water flux.

Ge et al. [65]studied draw solution leakage and energy requirements in draw solution recycling in FO processes. Using Polyelectrolytes as draw solution produced high water flux with low reverse leakage compared to conventional ionic salt draw solutions. However, the main drawback of this experiment was the relatively high viscosity of diluted draw solution. Investigations of the effect of using fertilizer draw solution to evaluate the performance of FO processes have been studied experimentally by Phuntsho et al. [66]. Different chemical fertilizers have been tested as a draw solution where the diluted fertilizer draw solution will be used in fertigation, and this process is only applicable in agricultural aspects. Higher water flux was achieved with soluble fertilizers that can produce higher osmotic pressure than seawater. Yu et al. [67] experimentally investigated the impact of using ferric-lactate (LAFe) complex as draw solution, which had a moderate viscosity and high solubility. The obtained water flux was 18.78 LMH with (1 M) LAFe and it significantly improved compared to (1 M) NaCl draw solution. Using LAFe has a positive impact on FO performance due to its high osmotic pressure. Ling et al. [68] discussed the impact of using magnetic nanoparticles as novel draw solute. It was verified that using such draw solution leads to high driving force and subsequently gives better water flux. The major drawback of this experiment is the agglomeration of diluted draw solution.

2.3.2 Concentration Polarization (CP)

Considering the first orientation the membrane active dense selective layer is confronting the draw solution as in the (DS-AL) operation mode. While, the other membrane orientation is where membrane active layer is in front of the feed solution just like the condition of FO desalination [54]. Moreover, in the afore-mentioned membrane orientations, the theoretical driving force in the operation is considerably greater than the real driving force. Thus, the actual membrane flux is lower than the one calculated by the equation [65] [69]. Such reduction in membrane flux is linked with the concentration polarization (CP) existence due to the fact that FO membrane is asymmetric [70] [62] [54] [71]. Concentration polarization has been looked at as a challenging and unavoidable forward osmosis process phenomena. There are two effects of the concentration polarization in forward osmosis membrane. Firstly, the increase in the feed solution concentration as well as its osmotic pressure at the active selective layer due to permeation of water across the draw side. Second effect is the reduction in draw solution concentration and osmotic pressure at the active layer due to the dilution of draw solution close to the active layer caused by permeation of water. Hence, the equation of membrane flux must be adjusted in order to consider this effect [65] [54].

$$J_w = A\sigma\Delta\pi_{effective} = A\sigma(\pi_{Draw,a} - \pi_{Feed,a}) \qquad (2.9)$$

Where $\pi_{\mathrm{Draw,a}}$ and $\pi_{\mathrm{Feed,a}}$ are the osmotic pressures of draw and feed solutions at active FO membrane layer. Furthermore, $\Delta\pi_{\mathrm{effective}}$ is the real driving force in forward osmosis that is considerably less than $\Delta\pi_{\mathrm{Bulk}}$.

2.3.2.1 External Concentration Polarization (ECP)

Similar to all membrane driven processes ECP exists in the membrane dense selective layer. However, the two types of ECP in forward osmosis depend on membrane orientation. The phenomena would be concentrative external concentration polarization (CECP) when the active dense selective layer faces the feed solution, as in FO desalination. Whereas, a dilutive external concentration polarization (DECP) as in (DS-AL) operation mode would be considered if the active layer of membrane is facing the draw solution.

CECP takes place since the accumulation of solute is close to the active layer as a result for permeation of water from the feed side to draw side. Such accumulation leads to a drop in the net osmotic pressure. Hence, membrane flux declined. Yet, when the active layer of the membrane is in front of the draw solution as in the (DS-AL) operation mode the external concentration polarization turn into dilutive in nature (DECP). For the CECP, DECP as well decreases the overall net osmotic pressure available for the FO system. However, the impact of ECP on water permeation could become less by manipulating hydrodynamic condition such as flow rate, turbulence or optimizing permeation flux rate [70] [62] [65] [54].

A sample that represents the membrane flux in the existence of CECP was developed by McCutcheon and Elimelech using the theory of boundary layer film in the equation below [72]:

$$\frac{\pi_{Feed,m}}{\pi_{Feed,b}} = \exp\left(\frac{J_w}{k_F}\right) \tag{2.9}$$

Where $\pi_{Feed,m}$ represents the osmotic pressure of the feed at the surface of membrane, and $\pi_{Feed,b}$ is basically the osmotic pressure of bulk feed solution. Thirdly, k_F demonstrates the mass coefficient on the feed side of the membrane.

While, when DECP was present, the membrane flux was modeled by the following equation:

$$\frac{\pi_{Draw,m}}{\pi_{Draw,b}} = \exp(\frac{-J_w}{k_D}) \tag{2.10}$$

The equation represents the osmotic pressure of the draw at surface of membrane as: $\pi_{Draw,m}$. Moreover, it shows the osmotic pressure of bulk draw solution and mass transfer coefficient on membrane draw side as: $\pi_{Draw,b}$ and k_D.

Mass transfer coefficient could be illustrated as:

$$k = \frac{ShD}{d_h} \tag{2.11}$$

Where Sh is the Sherwood variable, D represents the solute diffusion coefficient, and d_h clarifies the hydraulic diameter of channel flow.

2.3.2.2 Internal Concentration Polarization (ICP)

ICP is located within the support layer of asymmetric FO membrane. The orientation of membrane determines the case of ICP which is either dilutive or concentrative, just like ECP. Research organizations have concurred on the fact that the effect of ICP is one of major contributors to declination of membrane flux and a detrimental factor in the process of forward osmosis [72] [73]. Concentrative internal concentration polarization (CICP) occurs when the draw solution is faced by the membrane active layer such as the (DS-AL) operation mode. This phenomenon takes place at the interface with the active layer within the porous support layer due to accumulation of solute caused by permeation of water towards the draw solution. Similarly, CICP is the reason for membrane flux decline due to the reduction on the net osmotic pressure.

2.3.2.3 Concentrative ECP Coupled with Dilutive ICP

McCutcheon and Elimelech [72] recommended a model that predicts water flux when the feed solution faces the active layer just like FO desalination mode of operation

$$J_w = A\left[\pi_{D,b} exp(-J_w K) - \pi_{F,b} exp\left(\frac{J_w}{k_F}\right)\right] \qquad (2.12)$$

The equation illustrated experimental conditions and membrane parameters that lead to an easier water flux prediction. Moreover, it could be seen from the equation that both ECP and ICP contribute in a negative manner to the net osmotic driving force [72]. However, while using the high draw solution concentration an inaccurate model would be obtained as suggested by Tan and Ng [74]. The subsequent group (Tan and Ng) discussed a model by the usage of modified film model and the boundary layer theorem for the prediction of water flux. Their adjusted equations were able to give better predictions to the experimental water flux. Furthermore, the study has suggested that elevating cross flow velocity and temperature could decrease ECP effect [74]. However, the equations are complex and would need irrelevant solving when operating conditions and concentrations of draw and feed solutions are being changed. In addition, the model has limitation in which NaCl and KCL were used only as draw solutions [54]. Qin et al. study included modeling and pilot scale in which it suggested that since DICP is present, 99% of water permeate reduction and that water permeate flux could get better using draw solution that has higher diffusion coefficient and FO membrane that has thinner support layer [75].

Nowadays, Bui er al. developed a comprehensive model that illustrates CECP and DICP in FO mode of operations. Moreover, the model takes into account the solute transport resistances by the usage of thin-film composite (TFC) membrane [76].

$$J_w^{FO} = A\left\{\frac{\pi_{D,b} exp\left[-J_w\left(\frac{1}{k_D}+\frac{S}{D_D}\right)\right] - \pi_{F,b} exp\left(\frac{J_w}{k_F}\right)}{1+\frac{B}{J_w}\left\{exp\left(\frac{J_w}{k_F}\right) - exp\left[-J_w\left(\frac{1}{k_D}+\frac{S}{D_D}\right)\right]\right\}}\right\} \qquad (2.13)$$

Describing the equation as: S represents the structural parameter of membrane. D_D stands for the solute diffusivity in the draw solution, while B is the intrinsic solute permeability coefficient of the membrane.

2.3.2.4 Concentrative ICP Coupled with Dilutive ECP

Concentrative ICP coupled with dilutive ECP occurs when the active layer of the membrane is encountering the draw solution like the PRO mode of operation. Similarly, in the study of McCutcheorn and Elimelech [72] an orientation model has been developed and introduced as:

$$J_w = A\left[\pi_{D,b} exp\left(\frac{J_w}{k_D}\right) - \pi_{F,b} exp(J_w K)\right] \tag{2.14}$$

In which K represents the measure of easiness of solute diffusion into and out of membrane support layer, hence a measure of ICP severity is defined by [77] :

$$K = \frac{t\tau}{D\varepsilon} \tag{2.15}$$

In Bui et al. study [77], a comprehensive model for flux prediction in PRO mode of operations related to the nonzero hydraulic pressure gradient through the selective layer has also been suggested by the following equation:

$$J_w^{PRO} = A\left\{\frac{\pi_{D,b} exp\left(-\frac{J_w}{k_D}\right) - \pi_{F,b} exp\left[J_w\left(\frac{1}{k_F} + \frac{S}{D_F}\right)\right]}{1 + \frac{B}{J_w}\left\{exp\left[J_w\left(\frac{1}{k_F} + \frac{S}{D_F}\right)\right] - exp\left(-\frac{J_w}{k_D}\right)\right\}} - \Delta P\right\} \tag{2.16}$$

One of the main participants of membrane flux reduction in FO processes is concentration polarization [54] [69] [72] [78]. Several attempts were done to mitigate the impact of CP in FO membranes. Custom made draw solutes were used in previous studies, in which, they have high osmotic pressure due to their solubility and diffusion coefficients where it will decrease the effect of CP [79] [80]. The effects of operating conditions on CP were represented by many previous studies as summarized in table 1.

Table 1: *Overview of previous studies to mitigate the effect of CP in FO processes*

Studied parameters	Study approach	Findings	Ref.
Cross-flow velocity of laminar flow (m/s)	Modeling of simulated data	• Membrane flux has been enhanced and ECP decreased significantly due to increasing the cross flow velocity	[80]
Cross-flow velocity (m/s)	Modeling of simulated data	• Membrane flux has been increased and ECP decreased due to increasing of tangential flow across membrane	[81]
Feed solution and draw solution flow rate (cm^3/min)	Modeling of simulated data	• Membrane flux has been increased with high flow rate due to the decrease on ECP • Recovery rate has been decreased with high flow rate	[82]
0.1 and1.2 LPM FS flow rate and 0.4 LPM DS flow rate	Experimental study	• Membrane flux has been increased with high FS flow rate due to the decrease on CECP • Recovery rate has been decreased with high FS flow rate	[83]
Placement of Spacer	Experimental study	• Better membrane flux was achieved in (FS-AL) with adding spacer in feed solution channel away from the membrane • Similar membrane flux was also achieved in (DS-AL) but when the spacer was placed in touch with the membrane which is decreased DICP	[84]
Placement of Spacer	Modeling of simulated data	• Membrane flux has been decreased when the spacer was placed in touch with the membrane which creates a dead zone close to membrane location and results in an increase in the effect of CP	[85]

CHAPTER 3: EXPERIMENTAL SETUP

3.1 FO unit

Sepa CF forward osmosis has been used in this study, which is supplied by SteritechTM Corporation. The cell is made of stainless steel rectangular block in order to avoid corrosion from saline solutions. Moreover, since the material is stainless steel it could work with high flow rates safely that identifies industrial operation statues without any damage to the cell body. The outer dimension of the cell is 9 x 12 x 8.5 cm (3.5 x 4.72 x 3.34"). The cell is formed of two distinct compartments that will be detached by an FO membrane. One of them permits the flow of draw solution and other compartments are for feed solution. The FO membrane will be located between these two compartments and will contact the draw and feed solutions directly in order to allow for osmotic gradient to be developed inside the membrane and consequently separation of pure water will occur. Both draw and feed solutions will flow in a counter current flow direction due to the fact that this will provide more flux. One Sepa CF high fouling spacers with dimensions of 8 x 3.5 cm supplied by SteritechTM Corporation has been installed in feed side of FO membrane in order for turbulent flow to be provided when high flow rates are used.

The initial volume of both the draw and the feed solutions was 6.0 L each. Because of the batch operation condition used in this study, solutions after leaving the FO cell will be recycled back to the draw and the feed solutions tanks as in all experimental runs. However, FO unit has been operated for nearly 16 hours for each experimental run in order to assure that DS and FS have constant concentration. In this study, DS and FS concentrations have been modified and calibrated prior to start with another run. After the experimental run has finished, the membrane was removed from the FO channel and replaced with a new membrane to conduct a new run with a view to study the impact of different flow rates on FO performance, by changing the feed solution from DCW without treatment as shown in Figure 10, to settled and filtered DCW with and without adding a spacer in feed solution side.

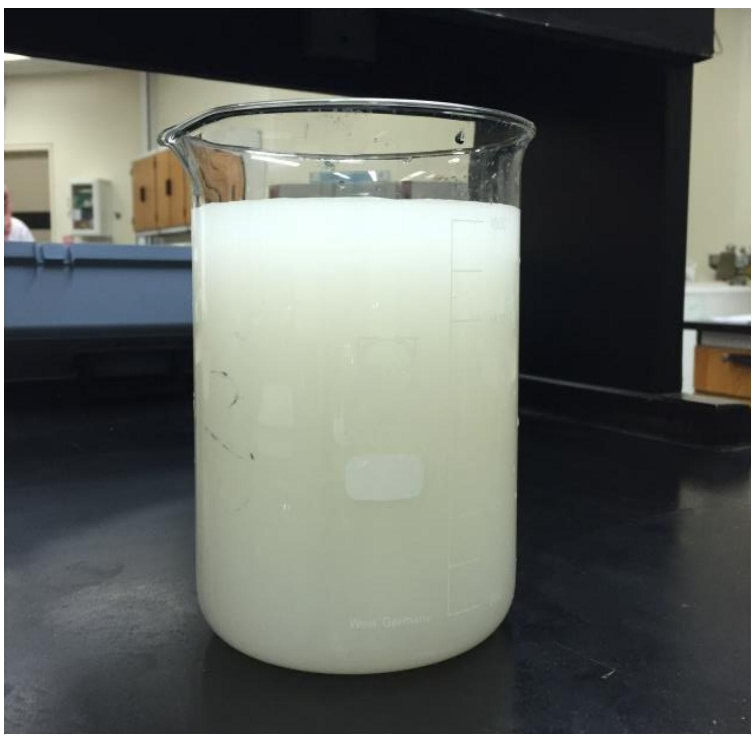

Figure 10: Dewatering construction water with high turbidity (300 NTU)

Several experimental runs were carried out based on different operation conditions by changing the following parameters:

- Flowrate of feed and draw solutions
- Membrane orientation (AL-FS) and (AL-DS)
- Adding and removing spacer
- Type of feed solution (DCW without treatment, Settled and Filtered)

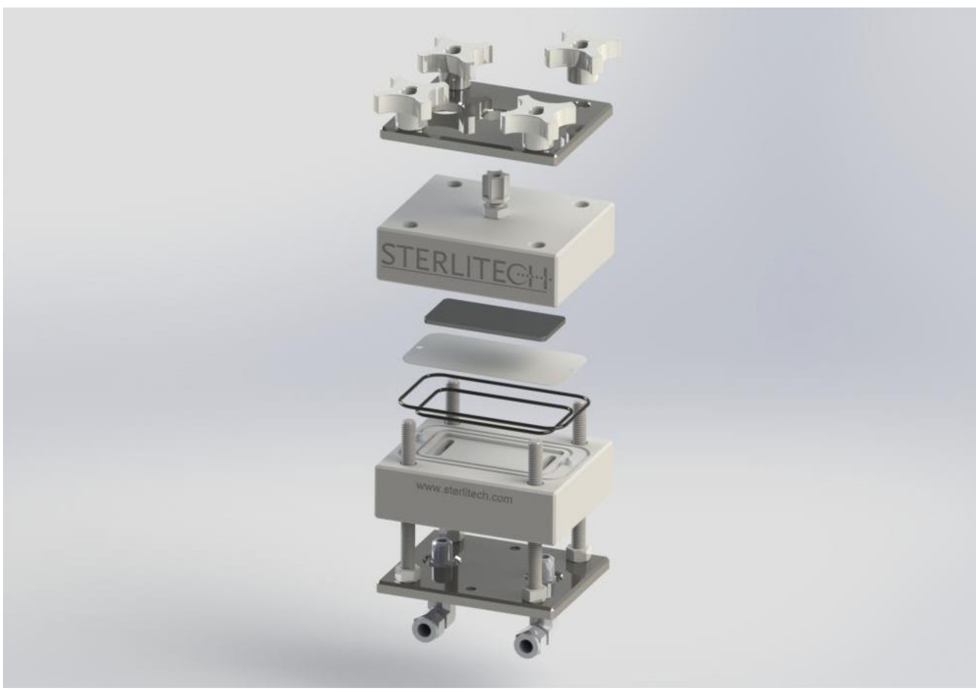

Figure 11: Sepa CF Forward Osmosis cell unit and the assembly of the unit. Adopted from http://www.sterlitech.com/membrane-process-development/cross-and-tangential-flow-test-cells/sepa-cf-cell.html

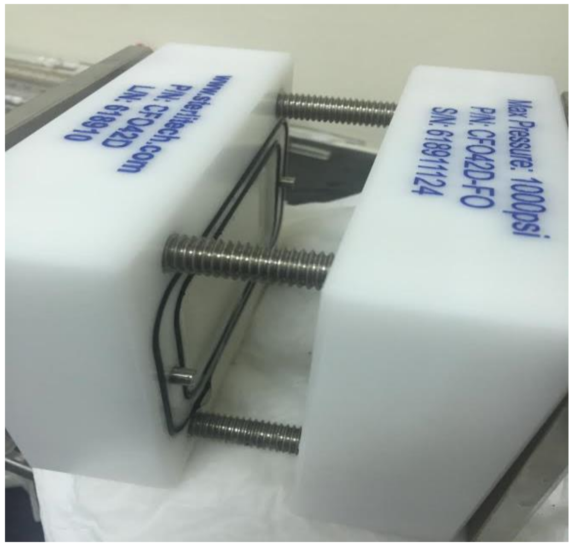

Figure 12: The two FO cell compartments. The left one is for the FS and the right one is for the DS separated by FO membrane which has a mesh spacer in feed side.

Two cup style feed tanks supplied by SteritechTM Corporation that have capacity of 2.4 gallon (9 L) made of stainless steel were used for dewatering construction water feed solution and 0.5M of NaCl draw solution. As mentioned before, forward osmosis bench-scale system unit was used to conduct experiments for this study. The system is selected and designed in a way that all operating conditions such as, flow rates, concentrations, change in the feed and the draw tanks weights can be easily monitored and controlled to obtain efficient results will high accuracy. Figure 13 show a picture of experimental set-up including the FO cell unit and all other auxiliary units and equipment used to control and monitor the system. While, Figure 14 depict a schematic diagram for the bench-scale FO system. Moreover, Two Cole-Parmer Micro-pumps A Mount Gear

Pump with Console Drive, PEEK Gears/PTFE seals were used to circulate and control the draw and the feed solutions flow respectively. The pumps can deliver pressure up to 80 psi. The maximum flow rate can be obtained is 0.84 GPM (3.2 LPM) at 5000 rpm. Tow site read panel mount Blue-White flow meters as well have been installed in the draw as well as the feed lines in order to measure and control the desired flow rates in both draw and feed sides. The flow meters reads a range between 0.1 – 1.0 GPM (0.38 – 3.8 LPM) which covers the high flow rates investigated in the study. However, to ensure proper maxing of the DCW suspended solids were achieved to investigate the impact of these colloidal particles on the membrane flux, one magnetic stirrer was placed under the tank of feed solution.

To prepare the desired NaCl solutions for draw tank, a balance supplied by aeAdam Company with a model number PGW 6002e has been used to measure NaCl salt weight. The maximum capacity of the balance is 6000 g and has a readability of 0.01 g. the pan size of the balance is 7.6×7.6" (192×192mm). Also an EW-11017-04 Ohaus Ranger™ Scale that has 12 kg (24 lb) capacity has been performed for the measurement of draw solution's weight difference. The scale has a pan size of 14" x 9.5" and a readability of 1 g. Furthermore, It was connected to PC through a wire to record the change of weight every 15 minutes throughout the total duration of the experimental run (16 hours). In addition, A 3/8" OD x .295" ID Type T Nylon tubing supplied by Steritech™ Corporation have been used to connect Sepa FO cell with other auxiliary parts and units. In order to measure conductivities of both draw and feed solutions, Agilent C5111 conductivity meter was utilized in this study to cover the wide range of draw and feed salinities. This conductivity meter can measure salinity range between 2 – 19990 µS/cm and temperature compensation ranging between 0 to 60 °C that is satisfactory for this study. The meter has a cell constant of 1.0±0.2 and probe diameter of 12 mm that is made of glass. For turbidity measurement A "2100 P TURBIDIMETER" supplied by HACH was used to measure the turbidity with Nephelometric Turbidity Units (NTU). The turbidity measurement is based on the effect of the suspended solids in an aqueous sample to the transmission of light and it has been obtained using a portable turbidity meter to ensure the quality of water that would be treated in this study.

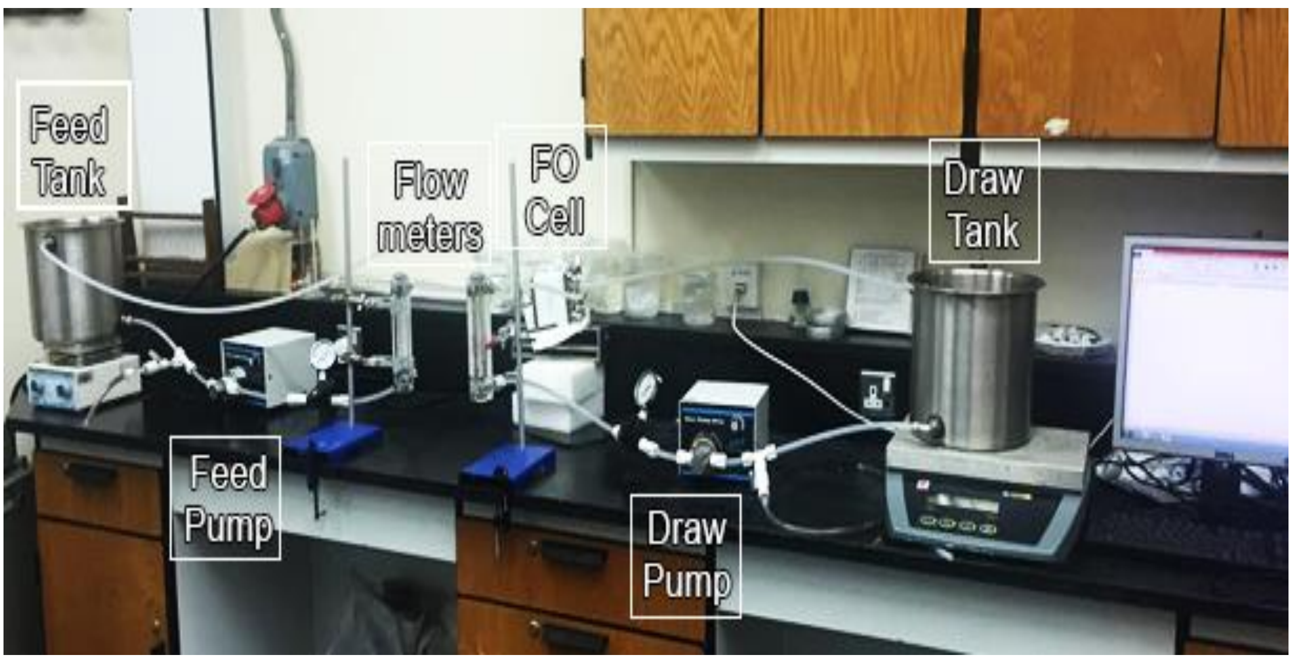

Figure 13: Bench scale of FO system used in the study

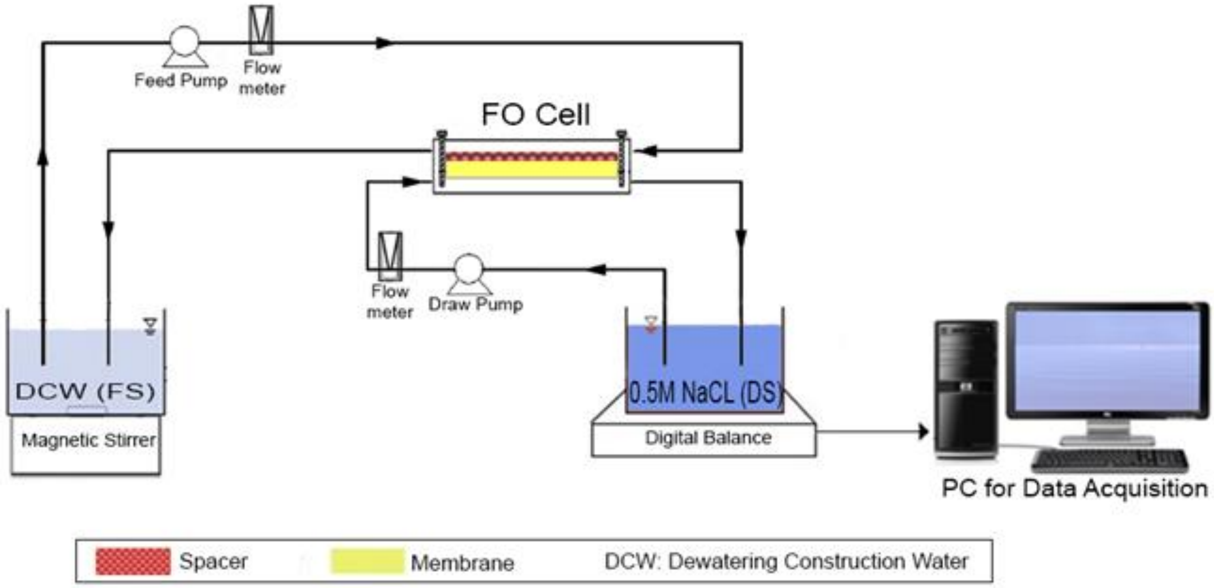

Figure 14: Schematic diagram for FO system used in the study

3.2 FO Membrane

This study uses the cellulose tri-acetate (CTA) forward osmosis membrane supplied by Hydration Technology Innovation (HTI). The membrane consisted of cellulose triacetate (CTA) active layer, which was a part of the polyester screen in order to raise the active layer efficiency. FO extensively uses this membrane due its advantageous properties such as: wide availability, low fouling tendency, mechanical strength and delivery of high water flux [86]. However, these membranes have low resistance to biological attack, and could be exposed to hydrolysis. Therefore, pH of feed and draw solution should be adjusted in the range of (4 – 7), and 35°C operation temperature [62] .The membrane was cut to fit the used FO cell. Dimensions of the membrane are 11.5 cm x 5.75 cm and with a thickness of 0.5 mm. At the beginning of each experiment the system and the membrane has been washed with 6 L of distilled water for two hours for both draw and feed solution tanks. This procedure took place just immediately before running each desired experiment. This process ensures that the pores of the membrane is opened and would be ready to start the run.

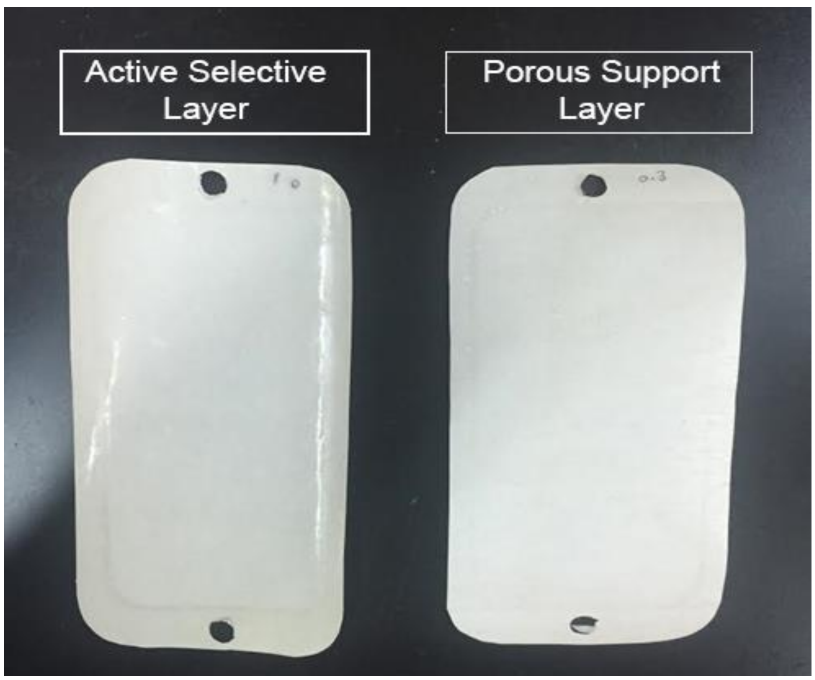

Figure 15: Active selective layer and porous support layer of used CTA membrane in FO system

Before employing the FO membrane to run the FO unit, a polymeric mesh spacer was added in the feed solution side in contact with FO membrane. A mesh spacer was utilized in this experiment to study and investigate the reduction of concentration polarization, enhancing the flow turbulence, avoiding membrane fouling and provide membrane support. The mesh spacer has a similar size to the used membrane in these experiments: its dimensions measured 8 x 3.5 cm with a thickness of 1 mm. As shown in Figure 16, the polymeric mesh spacer configuration.

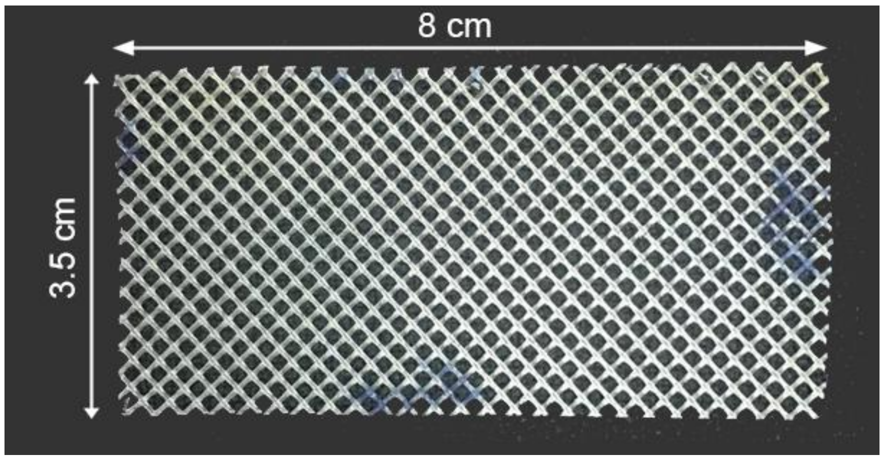

Figure 16: Polymeric mesh spacer

3.3 Draw and Feed Solutions

At the beginning of this study, different samples of dewatering construction water were collected from different locations within al-Saniya area in order to have reliable data to be analyzed as a feed solution. The main characteristics of these samples are summarized in table 2.

Table 2: *The analyed chemical parameters of DCW*

Parameter	Parameter Formula	Unit	Parameter	Parameter Formula	Unit
pH	pH	-	**Barium**	Ba	ppm
Turbidity	-	NTU	**Calcium**	Ca	ppm
Chemical Oxygen Demand	COD	ppm	**Cobalt**	Co	ppm
Alkalinity	ALK	ppm as CaCO3	**Chromium**	Cr	ppm
Bi Carbonate	$HCO3^{-}$	ppm	**Copper**	Cu	ppm
Total Solids	TS	ppm	**Iron**	Fe	ppm
Total Suspended Solids	TSS	ppm	**Potassium**	K	ppm
Total dissolved solids	TDS	ppm	**Magnesium**	Mg	ppm
Sulfate	SO4	ppm	**Manganese**	Mn	ppm
Chloride	CL	ppm	**Molybdenum**	Mo	ppm
Ammonia Nitrogen	N	ppm as N	**Sodium**	Na	ppm
Nitrate	N	ppm as N	**Nickel**	Ni	ppm
Nitrite	N	ppm as N	**Lead**	Pb	ppm
Hardness	= 2.497 [Ca, mg/L] + 4.118 [Mg, mg/L]	ppm	**Antimony**	Sb	ppm
Phosphors	P	ppm	**Selenium**	Se	ppm
Arsenic	As	ppm	**Strontium**	Sr	ppm
Boron	B	ppm	**Vanadium**	V	ppm
Electrical Conductivity	EC	µS/cm	**Zinc**	Zn	ppm

Table 3*: Chemical parameters of DCW collected from point 1*

Sample # 1	**DCW Collected From Point 1**				
Parameter (Unit)	**Obtained value**	**Parameter**	**Obtained value**	**Parameter**	**Obtained value**
pH	7.59	Nitrite - N	0.182	Mg	80
Turbidity	350	Hardness	1,273	Mn	<0.05
COD	17	P	1.22	Mo	<0.05
Alkalinity	149	As	<0.05	Na	297
($HCO3^{-}$)	181	B	0.6718	Ni	<0.05
(SO4)	1,020	Ba	0.0572	Pb	<0.05
(CL)	441	Ca	378	Sb	<0.05
Ammonia Nitrogen - N	1.615	Co	<0.05	Se	<0.05
Nitrate - N	3.1	Cr	<0.05	Sr	9.648
EC	3,456	Cu	<0.05	V	0.247
K	26.4	Fe	<0.05	Zn	<0.05

Table 4: *Chemical parameters of DCW collected from point 2*

Sample # 2	**DCW Collected From Point 2**				
Parameter	**Obtained value**	**Parameter**	**Obtained value**	**Parameter**	**Obtained value**
pH	7.63	Nitrite - N	0.157	Mg	85.8
Turbidity	50	Hardness	1,326	Mn	<0.05
COD	16	P	1.24	Mo	<0.05
Alkalinity	195	As	<0.05	Na	308.4
($HCO3^{-}$)	238	B	0.7134	Ni	<0.05
(SO4)	1,060	Ba	<0.05	Pb	<0.05
(CL)	500	Ca	389	Sb	<0.05
Ammonia Nitrogen - N	1.792	Co	<0.05	Se	<0.05
Nitrate - N	3.1	Cr	<0.05	Sr	9.722
EC	3,753	Cu	<0.05	V	0.263
K	27.5	Fe	<0.05	Zn	<0.05

Table 5*: Chemical parameters of DCW collected from point 3*

Sample # 3	**DCW Collected From Point 3**				
Parameter	**Obtained value**	**Parameter**	**Obtained value**	**Parameter**	**Obtained value**
pH	7.74	Nitrite - N	0.147	Mg	85.9
Turbidity	25	Hardness	1,335	Mn	<0.05
COD	12	P	0.52	Mo	<0.05
Alkalinity	185	As	<0.05	Na	313.2
$(HCO3^{-})$	226	B	0.717	Ni	<0.05
(SO4)	1,120	Ba	<0.05	Pb	<0.05
(CL)	502	Ca	393	Sb	<0.05
Ammonia Nitrogen - N	1.497	Co	<0.05	Se	<0.05
Nitrate - N	2.9	Cr	<0.05	Sr	9.922
EC	3,753	Cu	<0.05	V	0.267
K	27.6	Fe	<0.05	Zn	<0.05

0.5M NaCl draw solution that resembles seawater concentration was used in all experiments and the study was done to investigate the flow through CTA membrane from feed solution toward the draw solution under different flow rates with and without adding the spacer. On the other hand, for the feed solution, there were different samples that have been prepared to decide which type of dewatering construction water will give better recovery rate with lower membrane flux reduction. The samples includes: DCW without treatment, settled DCW and filtered DCW through multimedia filter. And the obtained turbidity values for the aforementioned samples were 300 NTU, 26 NTU and 24 NTU, respectively. Each sample has been experimentally analyzed for the sake of finding main parameters that should be considered before starting the FO process.

To assess the condition of dewatering construction water before being treated by FO unit, quality tests for water have been done. Analysis has been performed for three samples of feed solution to in order compare the results. The analyzed samples was done using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) and Ion Chromatography (IC) at Qatar University's labs. Also, total dissolved solids (TDS), total suspended solids (TSS) and total solids of the samples have been examined based on the initial particles concentration and the final particles concentration difference after drying the sample according to the following Equations:

$$TSS = \frac{(Weight\ 1 - Weight\ 2\ )x10^6}{volume} \qquad (3.1)$$

Where, Weight 1 is calculated through using filtration apparatus and stirring DWC samples on the filter paper and it will be placed in the oven for 120 minutes until it is dried, then value will be obtained. Afterwards, weight 2 will be measured by drying filter paper after washing by distilled water. The volume of sample is equal 50 mL. Then, TSS will be obtained in ppm.

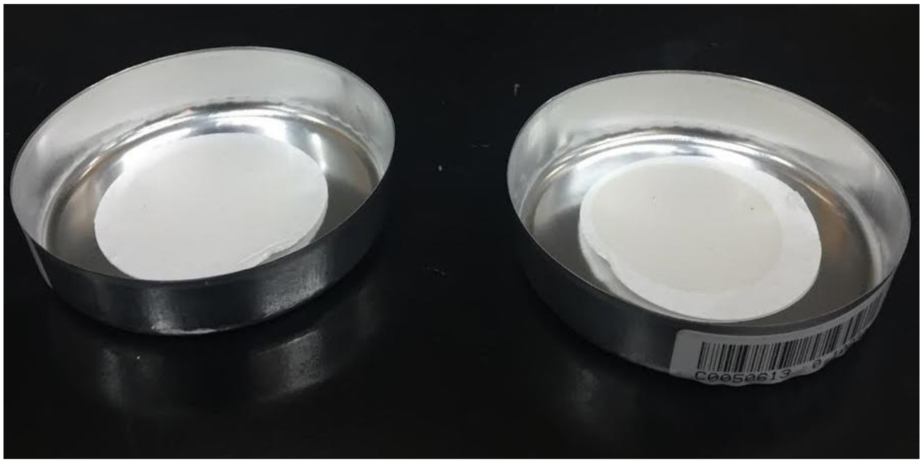

Figure 17: Drying filter paper used to calculate TSS

$$TS = \frac{(\text{Weight } 1 - \text{Weight } 2\ )\text{x}10^6}{\text{volume}} \qquad (3.2)$$

Where, Weight 1 is the weight of the dish and weight 2 is the weight of the dish with DCW after it has been in the oven 24 hours, until it is dried. The volume of sample is equal 50 mL. Then, TS will be obtained in ppm.

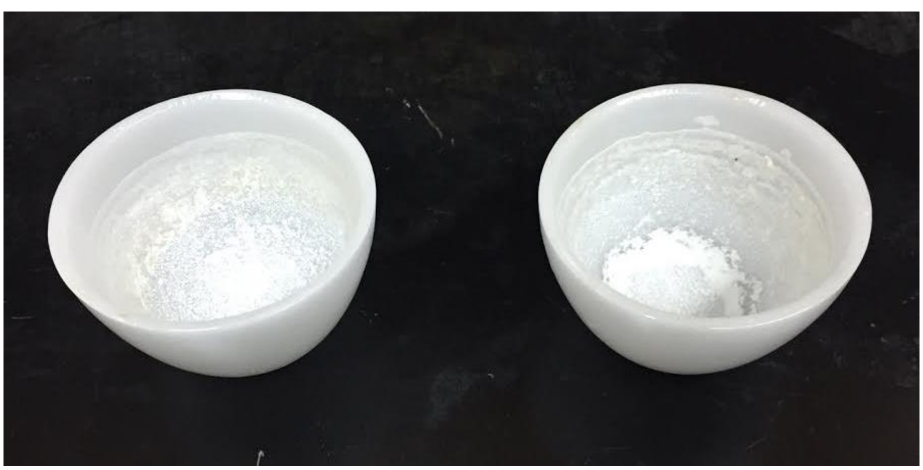

Figure 18: Dishes after drying in the oven

By subtracting the values of total suspended solids (TDS) from total solids (TS). The value of total dissolved solids (TDS) will be obtained in ppm according to the following equation.

$$\mathrm{TDS} = \mathrm{TS} - \mathrm{TSS} \qquad (3.3)$$

Following the afore-mentioned equations to calculate the values of TS, TSS and TDS. It was found that the values of DCW without treatment, settled and filtered for TS are 6,560 ppm, 6160 ppm and 6070 ppm, respectively. On the other hand, for TSS the value of untreated DCW was 325 ppm, while it was 45 ppm and 21 ppm for settled and filtered, respectively. Meanwhile, TDS has respective values of 6,235 ppm, 6,115 ppm, 6,049 ppm for DCW without treatment, settled and filtered.

3.4 Multimedia Sand Filter

In order to enhance the quality of dewatering construction water, a multimedia filters was utilized to filter the sample before being placed as a feed solution in the FO unit. Figure 19 shows the lab-scale multimedia sand filter used in this experiment. The filter was manufactured by ATICO in India. It consists of two tanks; one contains turbid water, and the other contains clean water to be used in the backwash process. The filtration media consists of 4 different layers with varying granular sizes; Activated carbon (anthracite) (0.8-1.6 mm), coarse sand (0.71-1.18 mm), fine sand (0.4-0.8 mm) and gravel. The height of each layer is 10 cm, 25 cm, 25 cm and 5 cm, respectively as shown in Figure 199. The filter can operate in two modes, the normal run mode and the backwash mode. The flow meter controls the discharge going into the system with values up to 5 LPM. As demonstrated in the figure 19, the valves can control the water flow direction for the normal run and the backwash mode. A Kirloskar Wonder 3 domestic pump was used to pump both the turbid and clean water into the system. It has a 0.37 kW and a 0.5 HP with a head varying from 6 m to 27 m.

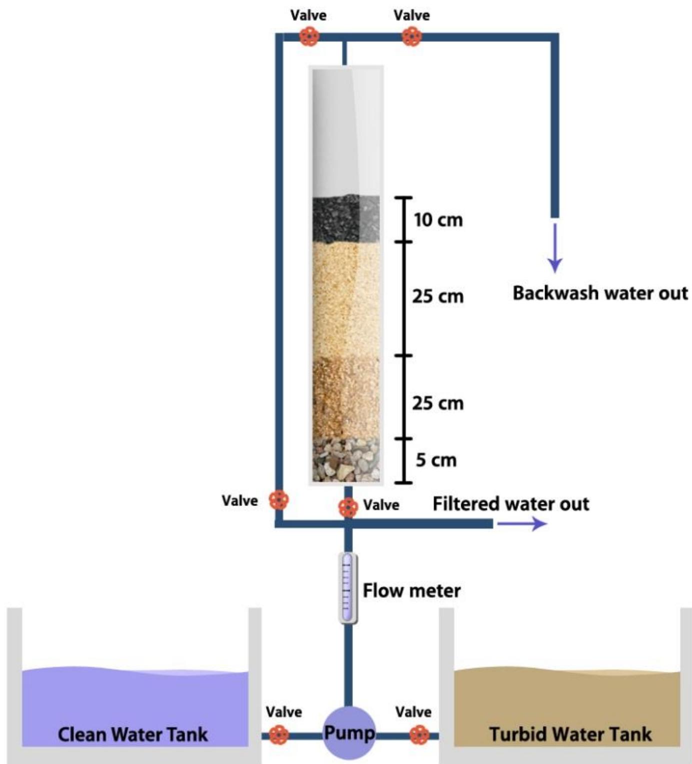

Figure 19: Multimedia sand filter unit

Before running the multimedia filters, the system has been backwashed for 20 minutes with 0.5 LPM flow rate. The backwash of the filter was done using clean tap water. The turbidity measurement was obtained using a portable turbidity meter. The filtration stage started by opening the filter flow valve to permit a constant flow to the filter at a 0.5 LPM flow rate. The recirculation valve was open to ensure a proper mixing during filtration in the influent tank, which is refilled, based on the need. After the filtration stage, water is collected from the effluent sampling port to be used in FO channel.

CHAPTER 4: EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Effect of Feed Solution and Draw Solution Flow Rate on Membrane Flux

Draw solution and feed solution flow rate effect on the membrane flux was evaluated using 35,000 ppm (0.5M) NaCl draw solution and 6,000 ppm dewatering construction water feed solution. The membrane active layer was facing the draw solution (DS-AL). The flow rates were in the range of (0.8-2.9) LPM without the use of spacer on the feed side. All experiments were performed at room temperature. The flow rate of FS was equal to the flow rate of DS at all times in order to eliminate any pressure effect. Moreover, each experimental run of this experiment was carried out for 1000 minutes (16 hours). Membrane flux across the membrane in the FO cell was calculated from the change in the weight of the feed solution tank using the following equation:

$$Jw=\frac{(W1-Wo)}{Am\ .t} \qquad (4.1)$$

Where, Jw is the membrane flux ($L/m^2.min$), W_1 and W_o are the first weight and weight at a specific time t of the draw solution, t is the time interval in minutes and Am is area of the membrane which is equal to 0.0042 m^2.

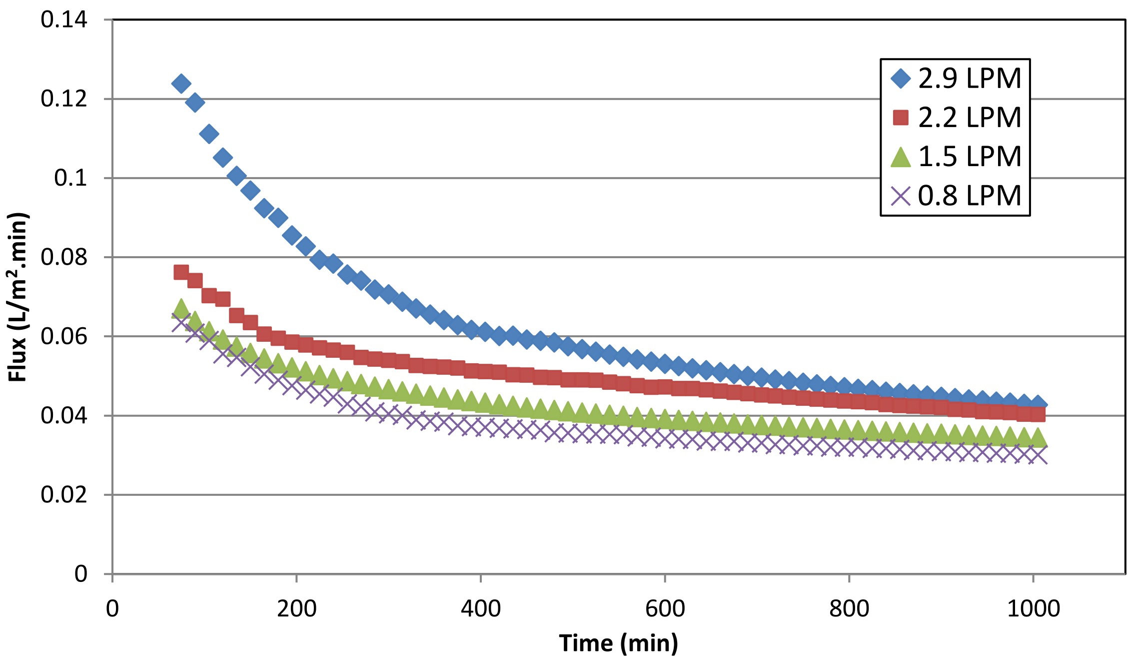

Figure 20: Membrane Flux under different FS and DS Flow rates, operation condition used are; 0.5 M NaCl DS, DCW FS, with no spacer

As shown in Figure 20 the membrane flux decreases over time. Moreover, the membrane flux decreased with the decrease of the flow rate of feed solution and draw solution. It could be seen from Figure 20 that the highest membrane flux was obtained at a flow rate of 2.9 LPM. The flux started at 0.13 L/m^2.min and dropped to 0.05 L/m^2.min after 1000 minutes. The membrane flux at a flow rate of 2.2 LPM started at 0.07 L/m^2.min and it decreased to 0.04 L/m^2.min. For the flow rates of 1.5 LPM and 0.8 LPM which have the lowest membrane flux where it went down from being 0.07 L/m^2.min at the beginning of the experiment to 0.03 L/m^2.min as run time reached to 1000 minutes.

External concentration polarization and internal concentration polarization lead to adverse effect during the FO filtration due to the fact that they decrease the effective osmotic pressure across the membrane, which has been investigated in previous studies [87].

Elevating the feed solution flow rate reduced the severity of dilutive external concentration polarization (DECP) and increased the flux of the FO membrane [88] [81] [89]. Technically, the concentration of feed solution at the interface of membrane solution decreased at high flow feed solution flow rate. Recent studies demonstrated that increasing feed solution flow rate helps in reducing the effect of external concentration polarization at the porous support layer [73].

Suspended solids that were presented in the dewatering construction water feed solution and placed against the porous support layer of the membrane might be accumulated in the porous support layer but did not move through the dense active layer of the membrane. The suspended solids from the feed solution were trapped within the internal structure of the membrane's support layer. However, the concentrative internal concentration polarization (CICP) occurs only when the draw solution is faced by the active layer in (DS-AL) operation mode. This action causes the (CICP) layer inside the support layer of the membrane which in turn substantially reduced the available net osmotic pressure on the system as well as declined in the membrane flux as shown in Figure 21 [73] [74].

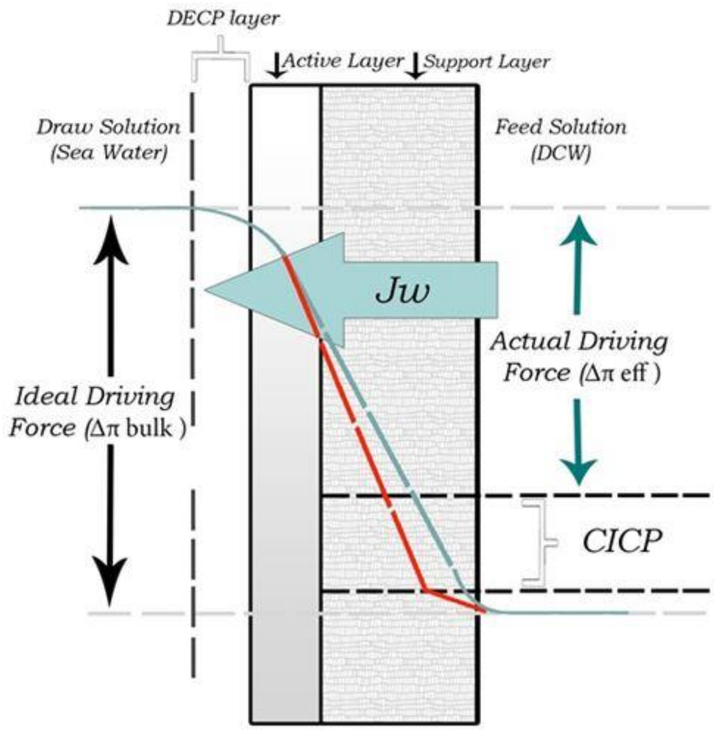

Figure 21: Illustration of the effect of membrane orientation (DS-AL) on the net osmotic pressure

It could be observed that once the flow rate of feed solution and draw solution increased, a noticeable increase in the membrane flux was achieved due to the fact that the mass transfer boundary layer which was closely placed with the membrane surface would become thinner. As a result, more mass was transferred at high flow rate and the dilutive external concentration polarization (DECP) was decreased [83] [90]. Furthermore, three factors would lead to higher membrane flux for the support layer that is facing the feed solution as shown in Figure 22 (a) Reduction in CICP and (b) Reduction in DECP, which are: reduction of suspended solids accumulation, enhancement of FS advection and reduction in the effect of CICP [73].

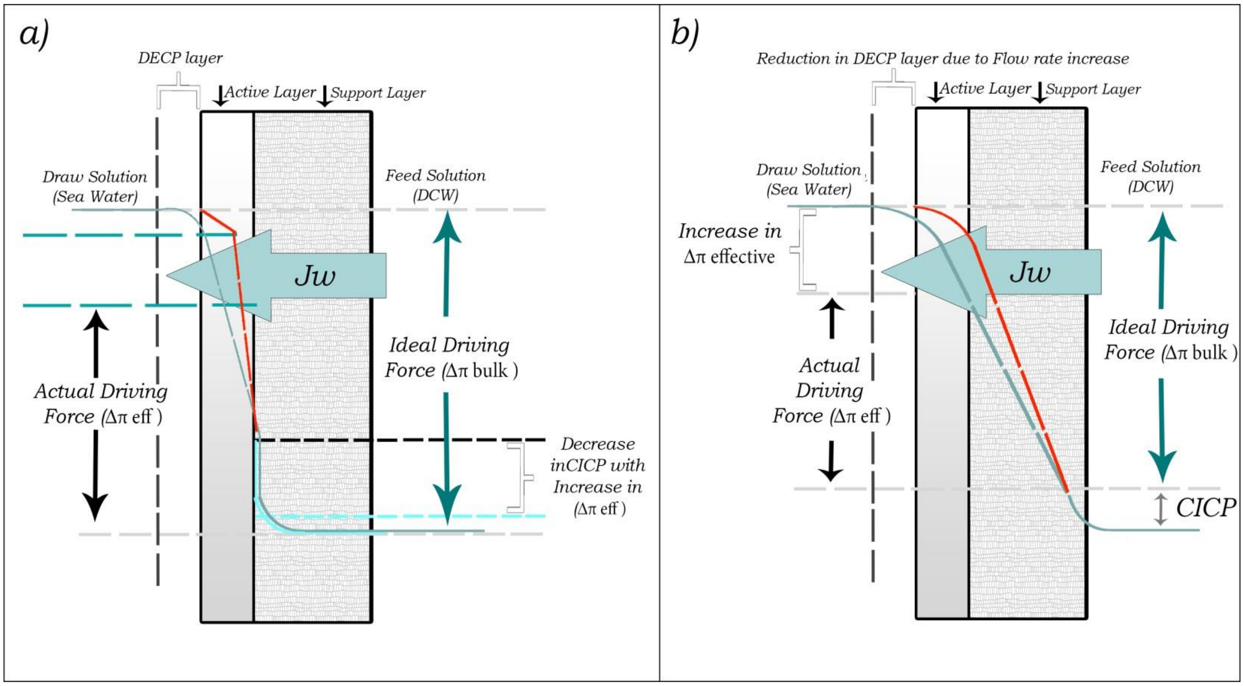

Figure 22: Illustration of increasing FS and DS flow rate in (DS-AL) operation mode, a) Reduction in CICP b) Reduction in DECP

As it could be seen effective Δπ was increased in Figure 22 (a) due to the reduction of CICP and also an increase occurred in the effective Δπ as shown in Figure 22 (b) since the flow rate increased and eventually the membrane flux has been enhanced. The membrane flux at low flow rate was significantly low due to the occurrence of ICP on the feed side. Furthermore, one of the major factors that played a role for flux reduction and lead ICP to take place was the colloidal particles in the feed solution that was accumulated inside membrane support structure.

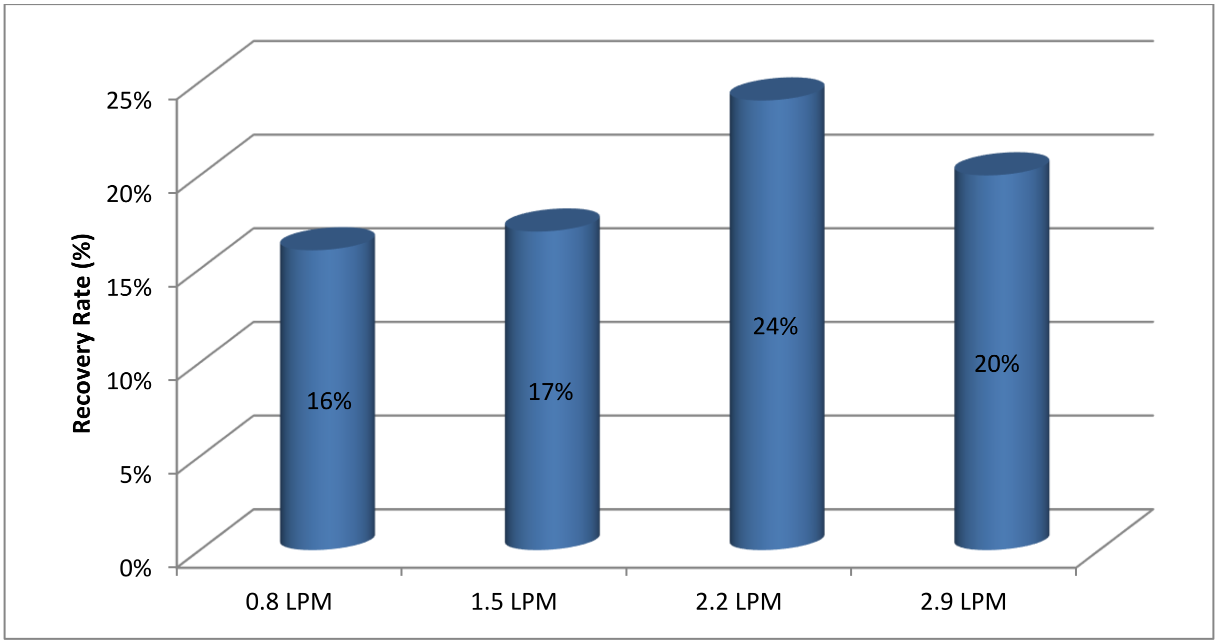

Figure 23: Recovery rate of different FS and DS flow rates, with no spacer

It has been also observed that with the increase of flow-rate from 0.8 to 2.9 LPM a noticeable increase in the recovery rate was noted. The recovery rate (%Ret) is the difference of weight that has been transferred through the membrane over the total time of the experiment and it was calculated using the following equation:

$$\%\mathrm{Ret} = \frac{(W_f - W_i)}{t} * 10^5 \qquad (4.2)$$

In equation (),W_f is the final weight that has been measured in the draw solution tank, W_i is the initial weight of draw solution and t is the time interval of the experimental run.

The highest recovery rate was indicated as 24% and was for the 2.2 LPM flow rate as it could be seen in Figure 23, this represented the maximum quantity of FS would pass through the membrane to DS followed by the recovery rate of 2.9 LPM flow rate which was equal to 20%. Also, Figure 23 illustrated minimum recovery rates which were 16% and 17% for flow rates of 0.8 LPM and 1.5 LPM, respectively. Hence, it can be seen that as flow rate increased the recovery rate increased and vice versa. This shows that when increasing the flow rate when FS facing the support layer increased the recovery rate and decreased the effect of concentration polarization at support layer of the FO membrane as shown in Figure 27. For 2.9 LPM flow rate, the high membrane flux probably accelerated the accumulation of colloidal particles at the membrane surface and reduced membrane flux due to membrane fouling.

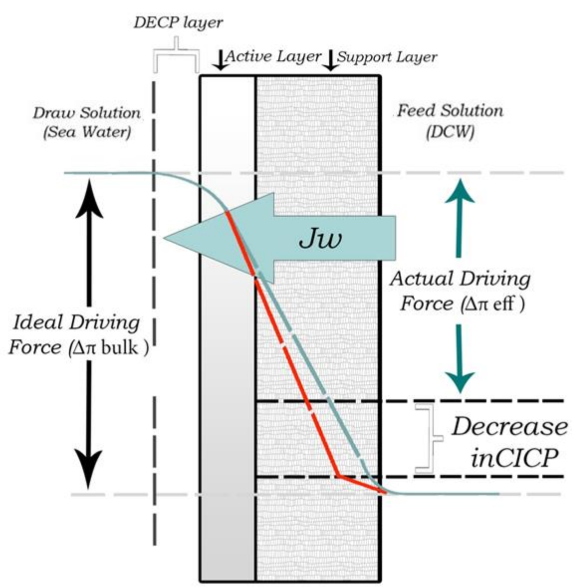

Figure 24: Illustration of the reduction in CICP with the increase of FS and DS flow rate in (DS-AL) operation mode

As shown in Figure 25, the minimum flux reduction percentage of 43% was obtained at a flow rate of 2.2 LPM with maximum recovery rate. At the higher flow rate of 2.9 LPM the recovery rate was 4% less than the recovery rate at flow rate of 2.2 LPM. Also, it was observed that at a flow rate of 2.9 LPM the flux reduction was 62% due to membrane colloidal fouling. The results demonstrated that increasing the flow rate would not necessarily enhance the membrane flux and 2.2 LPM flow rate was the optimum flow rate before colloidal fouling occurred.

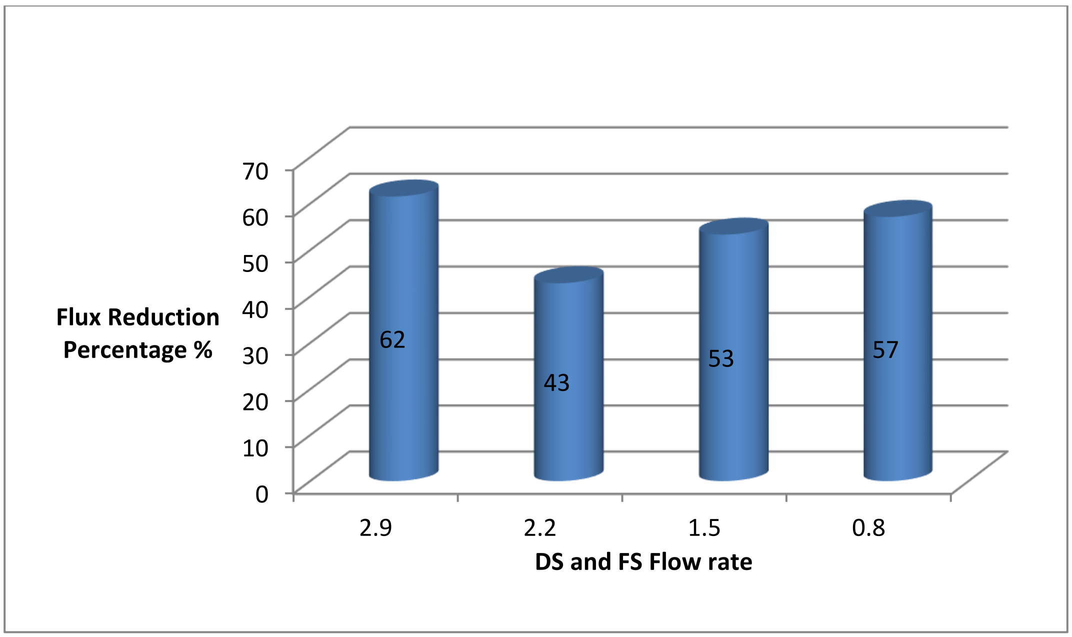

Figure 25: Flux reduction percentage under different FS and DS Flow rate, with no spacer

Concentration of suspended solids and other dissolved solids in the feed solution, probably led to both film formation on the surface of membrane and inorganic scaling. Furthermore, based on the relatively high solute concentration that presented in the draw solution, a higher ECP on the surface of membrane active layer would be more significant [91].

4.2 Effect of the Placement of Spacer on the Feed Solution Side

To study the effect of concentration polarization on the membrane flux, experimental runs were conducted by using different flow rates for the same sample of feed solution and draw solution. The membrane active layer was facing the draw solution, whereby membrane support layer was facing the feed solution. Moreover, a spacer was placed on the feed side of FO channel and in contact with the membrane support layer. Figure 26 shows the change of membrane flux with time.

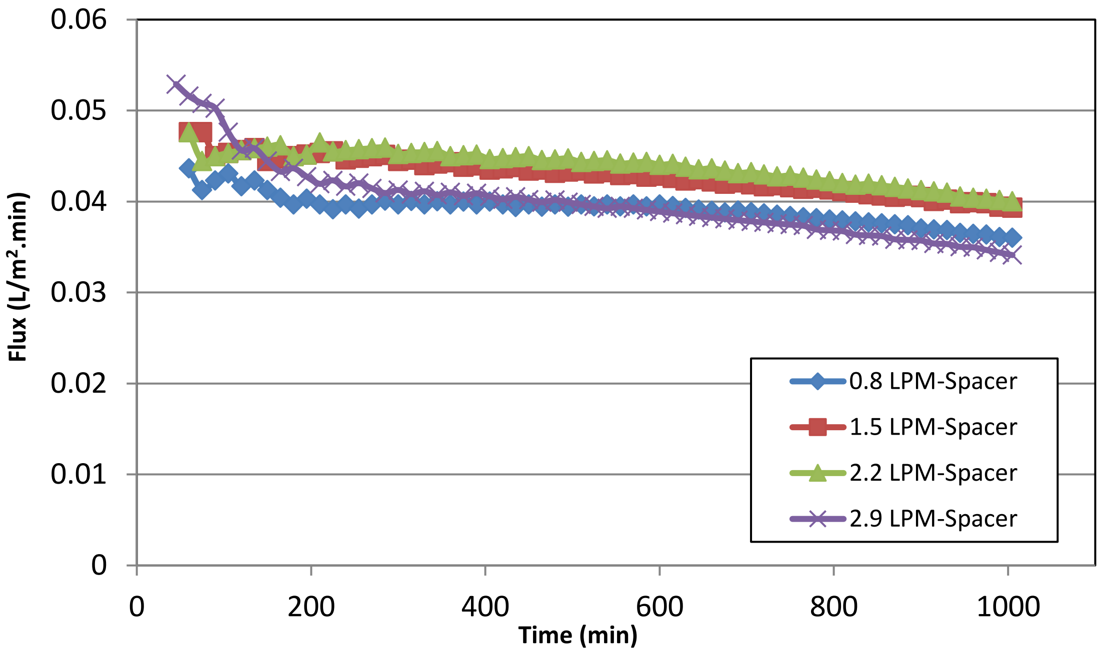

Figure 26: Membrane flux under different FS and DS Flow rates, operation condition used are; 0.5 M NaCl DS, DCW FS, with adding spacer in the feed solution side

As shown in Figure 26 the highest membrane flux was found at flow rate of 2.9 LPM and it started with 0.055 L/m^2.min and reduced to 0.035 L/m^2.min after 1000 minutes. For the membrane flux of 2.2 LPM and 1.5 LPM, this has almost the same decreasing trend which started at 0.048 L/m^2.min and decreased to 0.04 L/m^2.min. It could be seen also from Figure 26 that the lowest membrane flux was obtained at flow rate of 0.8 LPM. The flux started at 0.044 L/m^2.min and dropped to 0. L/m^2.min after 1000 minutes. The membrane flux for the 2.9 LPM flow rate decreased to the lowest rate after 1000 minutes, this sharp drop probably is caused by the high initial flux that encouraged the deposition of colloidal particles and decreased membrane flux even to less than that for 0.8 LPM flow rate.

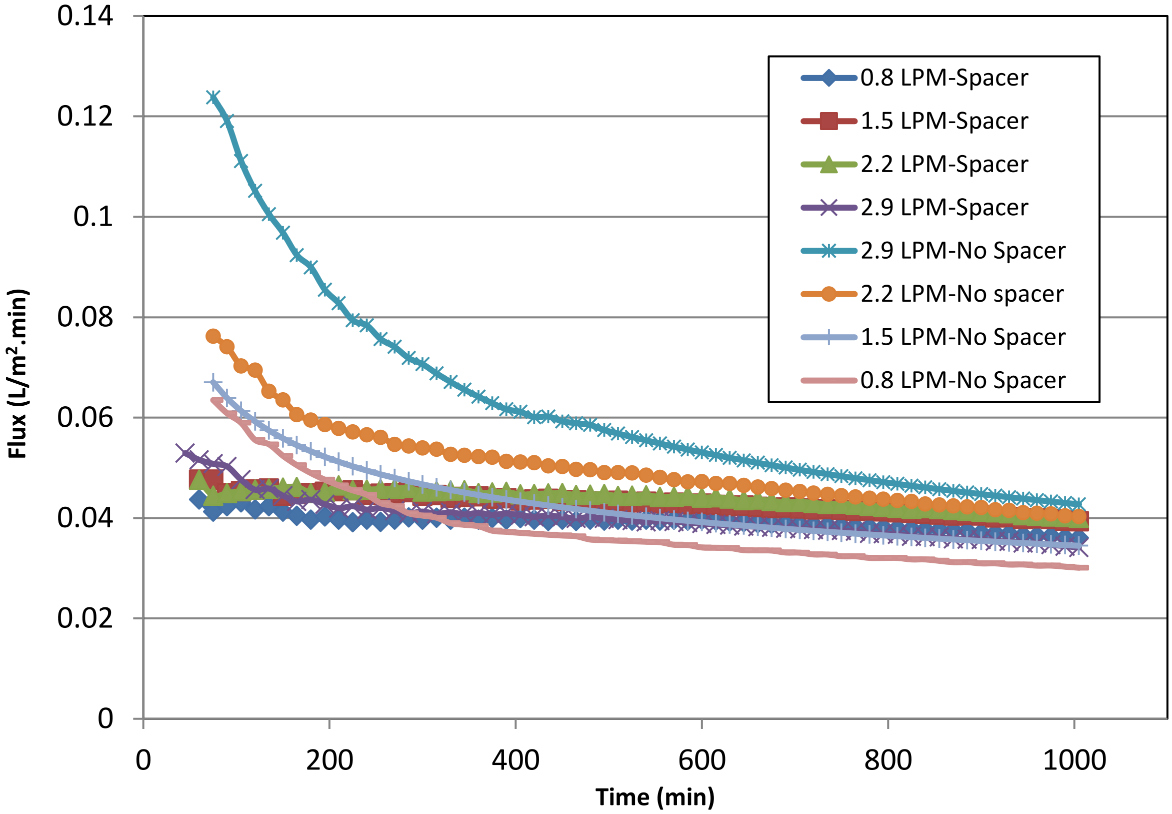

Figure 27: Membrane flux of CTA membrane with spacer and with no spacer

As shown in Figure 27 After combining the membrane flux of different DS and FS flow rates with and without the use of spacer it was concluded that without the use of spacer the FO process started with a higher flux value compared with the computed flux with the presence of spacer. However, without spacer a sharp flux drop occurred and caused same of membrane flux to reach the same level of that with adding the spacer after 1000 minutes. Hence, membrane would be subjected to fouling faster when the spacer was used. This was probably due to colloidal particles fouling which trapped between the spacer and the membrane surface and promoted membrane fouling in the case of spacer. On the other hand, as it was illustrated in Figure 27, membrane flux with the use of spacer had almost the same trend of flux decrease for the four flow rates. Therefore, the reduction percentage for such case would be less than that for a no spacer experiments. Also, it could be observed that membrane fouling for these flow rates has less fouling tendency compared with flow rates without placement of spacer.

The results reveal membrane flux with placement of spacer, it could be explained that membrane fouling for high flow rates (2.2 LPM and 2.9 LPM) has less fouling propensity than other flow rates (0.9 LPM and 1.5 LPM) with the use of spacer. Also, it could be concluded that the reduction in membrane flux was associated with colloidal particles entrapment due to the variation of flow rates. When a NaCl of 0.5 M was used as the draw solution both CICP and DECP happened at the active and support layer of the used membrane. Moreover, the water flux improved when the spacer was located in the feed side of the channel and in contact with the membrane support layer. Moreover, it has been illustrated that the used flow rates had only a slight impact on DECP. Thus, the main reason for such differences of membrane flux was associated with the impact of CICP. Along with the data obtained in (DS-AL) operation mode the location of spacer in the feed solution side raised inlet solution turbulence with less particles accumulation which has caused CICP mitigation [92].

Placement of spacer in (DS-AL) operation mode obviously depends on spacer symmetric and location in which channel it will be employed. At the dewatering construction water feed solution, the ECP in the feed solution side could be insignificant when dealing with solute movement across the membrane. Moreover, adding a spacer in the feed channel should somehow mitigate the overall concentration polarization by decreasing the ECP in the feed side. As a result, the membrane flux with a similar arrangement of the spacer in (DS-AL) operation mode will increase [85].

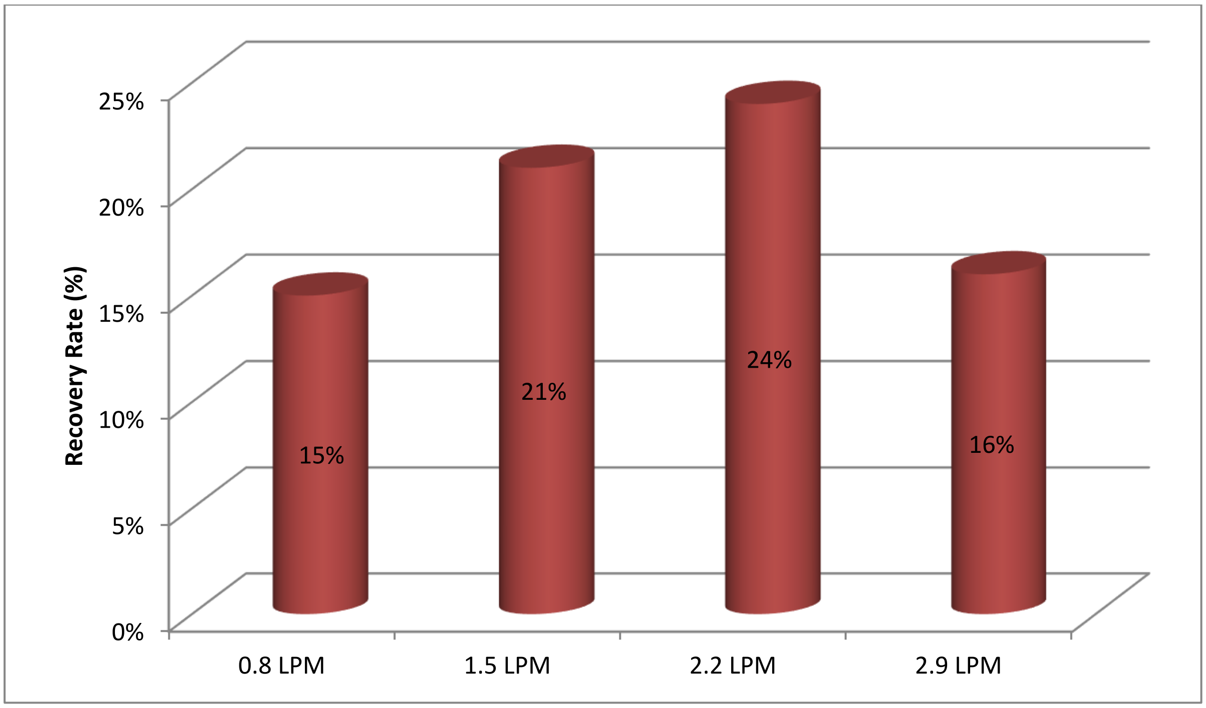

Figure 28: Recovery rate of CTA membrane with spacer under different FS and DS flow rates

It could be inferred for Figure 28, that the highest recovery rates were specified as 21% and 24% which were placed at 1.5 LPM and 2.2 LPM flow rates, respectively. Furthermore, the obtained recovery rate at flow rate of 2.9 LPM that was closely similar to the minimum recover rate with a value of 16%. However, the lowest value of recovery rate was for the flow rate of 0.8 LPM with a value of 15%. Hence, it can be understood that as flow rate increases with the use of spacer, its recovery rate would increase up to a certain value. Otherwise, with higher flow rate, like 2.9 LPM a clear decrease will be occurred as a result of more colloidal particles entrapment.

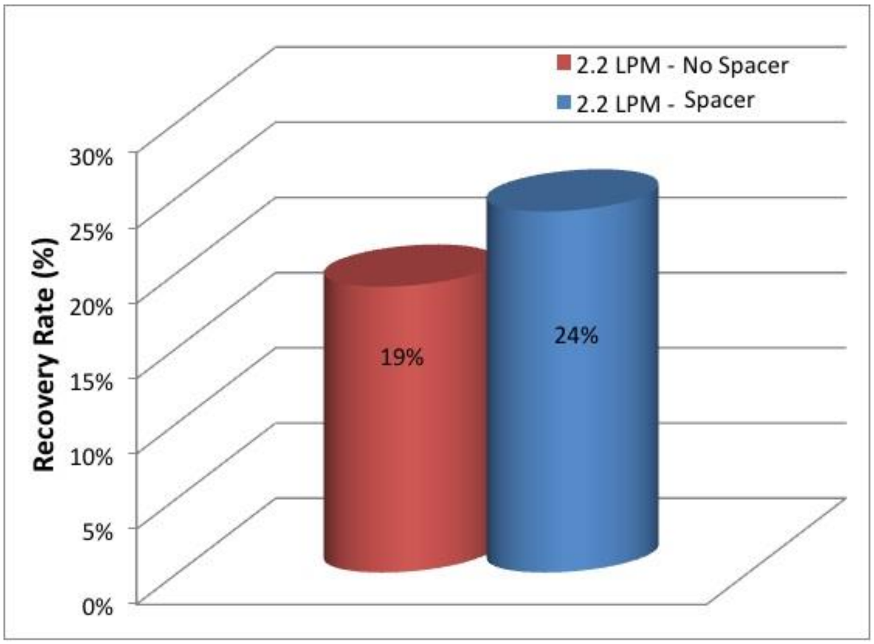

Figure 29: Recovery rate of CTA membrane with spacer and without spacer at 2.2 LPM flow rates

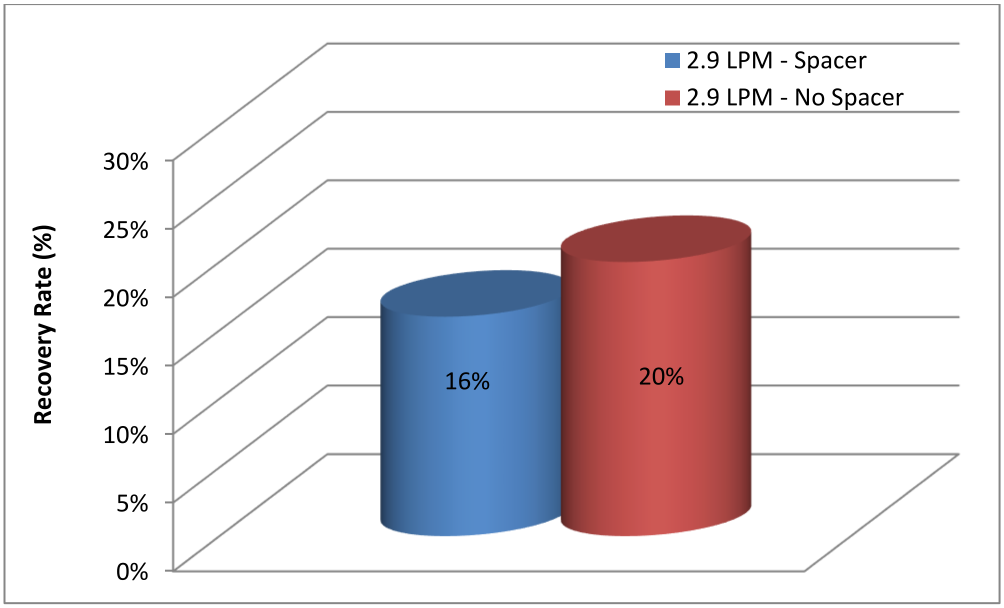

Figure 30: Recovery rate of CTA membrane with spacer and without spacer at 2.9 LPM flow rates.

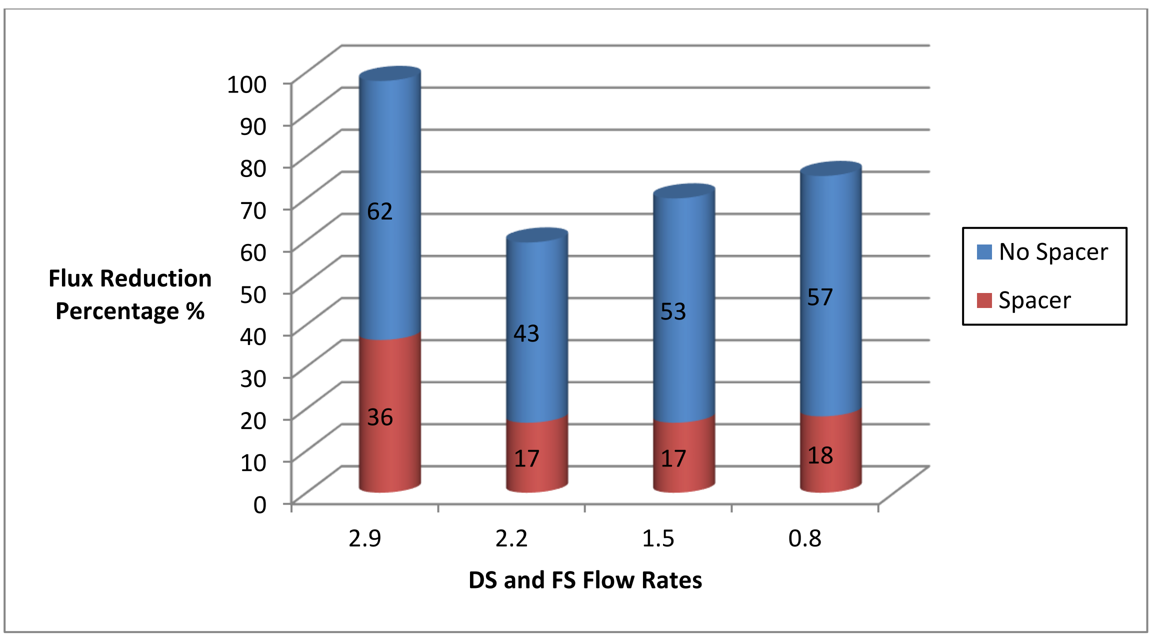

Figure 31: Flux reduction percentage of different DS and FS flow rate with and without spacer

As discussed previously with higher flow rates there was a high initial flux that would increase the conductive flow through the membrane and increase fouling on the feed side. Also, it can be understood that as flow rate increases with the use of spacer its recovery rate would decrease as a result of colloidal particles deposition on membrane surface as shown in figure 32. It could be seen that when spacer was added over the membrane in the FO feed channel with 2.2 LPM and 2.9 LPM flow rates the conductive flow towards the membrane surface has been increased. However, the recovery rate for flow rate of 2.2 LPM give better membrane flux and recovery rate comparing with 2.9 LPM flow rate.

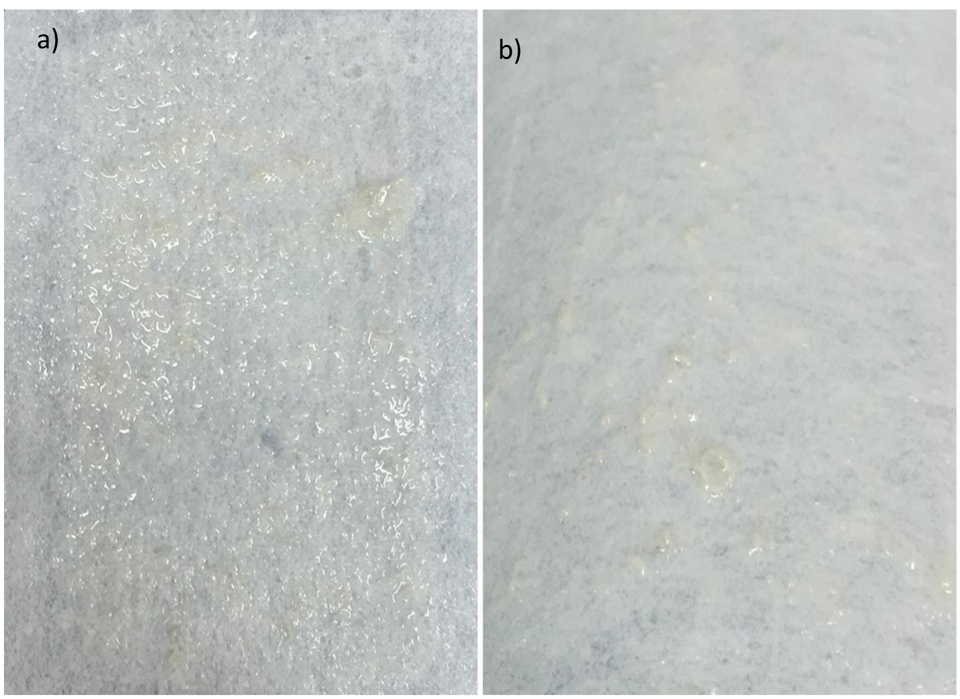

Figure 32: Colloidal particles accumulation on membrane Surface at flow rate of: a) 2.2 LPM b) 2.9 LPM

Flux reduction of the four flow rates were in range of 43-62% without placement of spacer. Among them, 2.2 LPM has pointed a relatively low flux reduction 17% with using a spacer, while reduction percentage of 2.9 LPM was the highest with a value of 36%. Both of 0.8 LPM and 1.5 LPM flow rates have almost the same value of reduction percentages which are 18% and 17%, respectively. The porous and rough structure of membrane support layer caused this phenomenon, in which it could lead the suspended solids to easily deposit on the surface of supporting layer in (DS-AL) mode [93]. Hence, it would produce severe internal concentration polarization that elevated the diffusive driving force toward draw solution, leading to higher flux reduction percentage [94] [95] as illustrated in Figure 33.

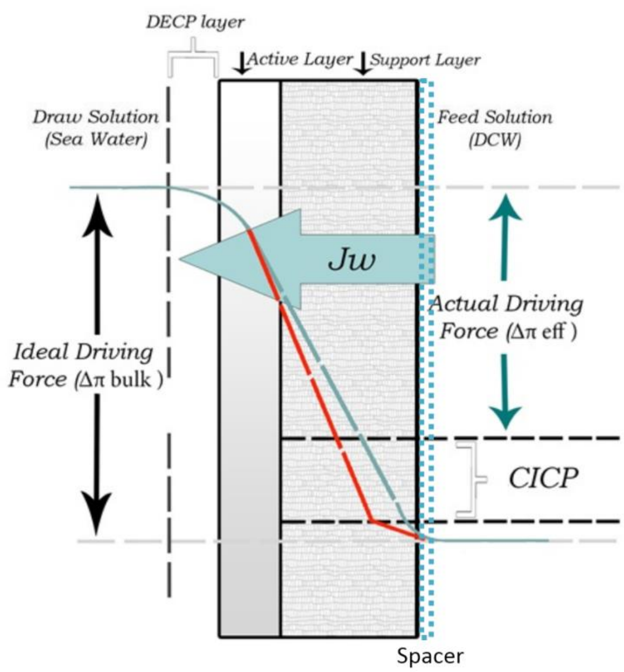

Figure 33: Illustration of produced ICP at flow rate of 2.9 LPM

However, when spacer was added the decline in membrane flux was less than that in the experiments without spacer. However, the recovery rate of FO process was directly affected by the membrane flux, higher initial membrane flux resulted in sever flux reduction. This was firstly due to the dilution of draw solution and reducing the osmotic driving force across the membrane. Secondly, due to colloidal particles acclamation which fouled the membrane and reduced membrane flux. Spacer was useful in the case of 0.8 LPM and 1.5 LPM flow rate which demonstrated high FO recovery rate whereas at 2.2 LPM and 2.9 LPM flow rate FO without spacer achieve higher recovery rate than with spacer. Hence, no need to use spacer at high flow rate. It should be noticed that highest recovery rate for FO experimental runs with and without spacer was in the case of 2.2 LPM flow rate. Based on this consideration, the difference in membrane fouling between experiments that were carried out with and without adding spacer could be illustrated as shown in Figure 34. It was confirmed that the flux drop has occurred due to colloidal particles entrapment during the filtration. The SEM analysis confirmed the entrapment formed at the surface of CTA membrane. Where SEM short for scanning electron microscope is a technology that emits high energy electrons on the surface of a sample to generate high resolution images of the sample grains, size, crystalline structure, texture and orientations, covering areas ranging from 1 cm to 5 microns in width.

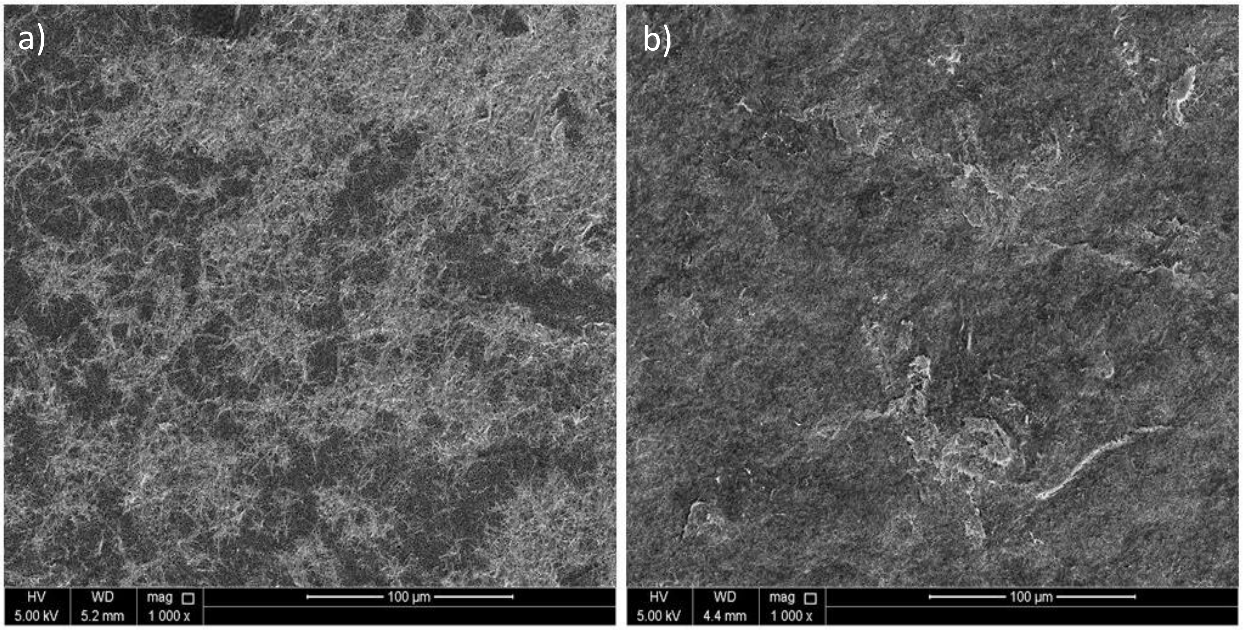

Figure 34: SEM analysis a) 0.8 LPM for dewatering construction water without using spacer, b) 0.8 LPM for dewatering construction water with adding spacer in the feed channel

In this research, it was proved that the placement of spacer in the feed channel could affect the liquid flow velocity and yield turbulence. Hence, it has been suggested that the turbulence generated from adding the spacer would disturb the surface of membrane's boundary layer and then urged suspended solids to spread from the support layer into feed solution, which decreased suspended solids diffusive driving force over the membrane structure toward the draw solution [92]. The intended graphical mechanism is illustrated in Figure 35. Therefore, the increase of water flux was predicted when spacer was utilized since it has been considered that resulted turbulence would mitigate the concentration polarization. Thus, flux would be enhanced.

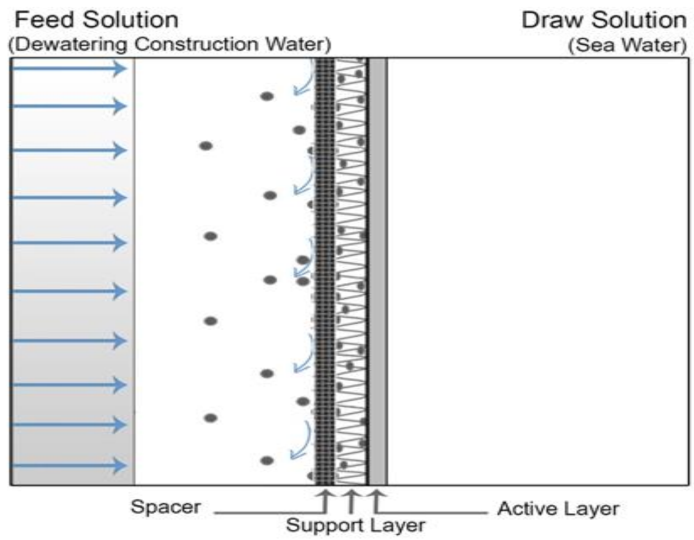

Figure 35: Illustration for the impact spacer that will urge suspended solids to spread from the support layer into feed solution, which decreased suspended solids diffusive driving force toward the draw solution

4.3 Effect of Pretreatment

4.3.1 Effect of Settling on Membrane Flux

In order to enhance the performance of the FO processes for the treatment of Dewatering construction water, settling tank was employed for the removal of suspended solids from the feed solution. Where in settling tanks the suspended solid (SS) that are heavier than water settle out at the bottom of the tank by gravitational sedimentation. Particles with a greater density settle faster than particles with lower densities [96]. After settling process for one hour detention time a turbidity value of 26 NTU was attained to start the experimental run. Membrane flux was evaluated using (0.5M) NaCl draw solution and settled dewatering construction water feed solution. The membrane active layer was facing the draw solution (DS-AL). The flow rate was 0.8 LPM with adding spacer on the feed side. All experiments were performed at room temperature for 16 hours (1000 minutes).

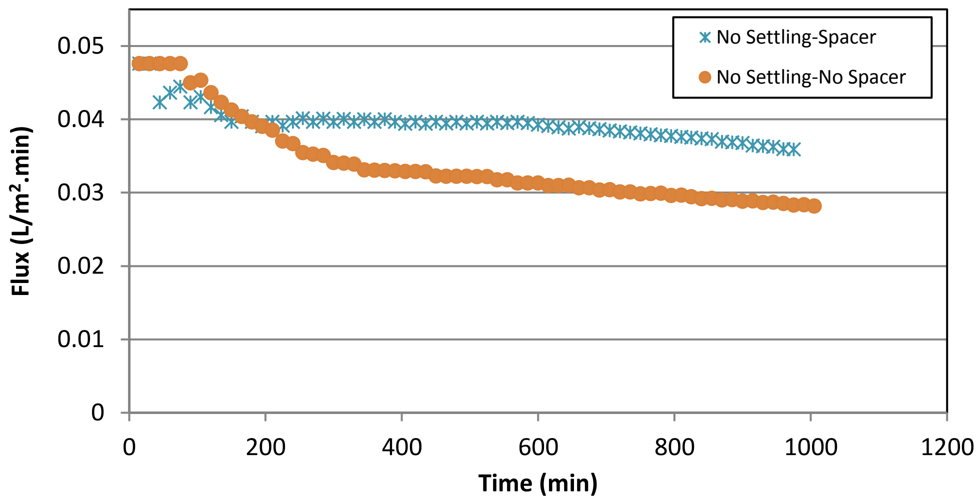

Figure 36: Membrane flux for DCW (Turbidity of FS = 300NTU), with and without spacer at 0.8 LPM Flow rates

As shown in Figure 36, the membrane flux of dewatering construction water without treatment decreased with time. It could be seen that the membrane flux for both cases (with and without spacer) started at 0.048 L/m^2.min and dropped noticeably to 0.03 L/m^2.min for the FO without placing the spacer in the feed side. However, when spacer was added the membrane flux dropped to 0.036 L/m^2.min after 1000 minutes.

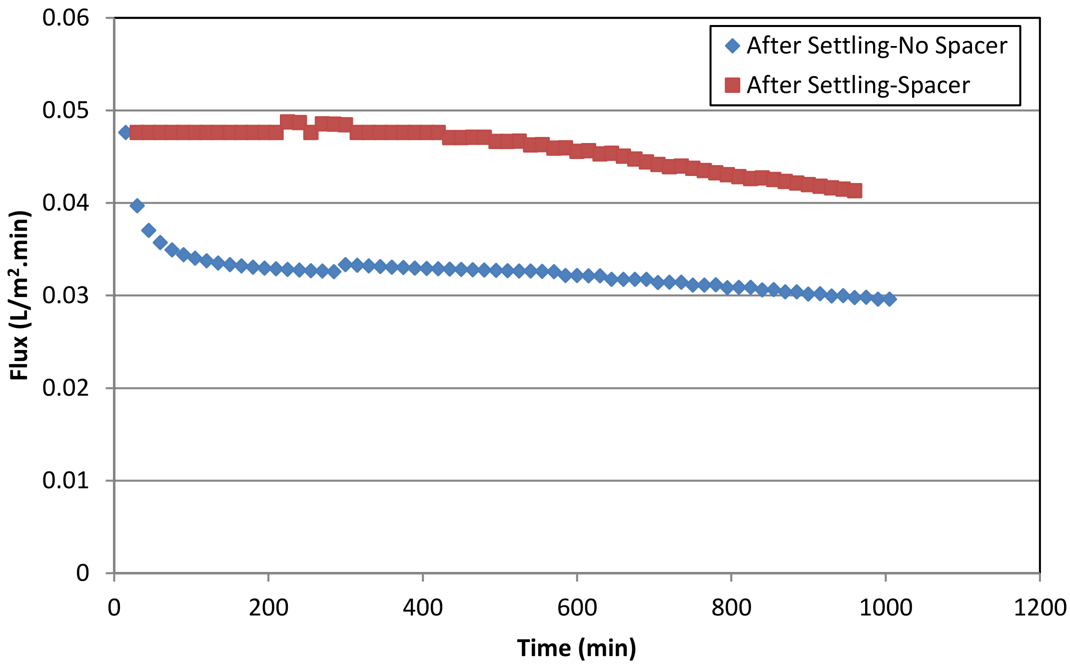

Figure 37: Membrane flux after settling (turbidity of FS = 26 NTU), with and without spacer at 0.8 LPM flow rates.

It could be seen from Figure 37 that the highest initial membrane flux value was for settled DCW. The membrane flux started at 0.048 L/m^2.min and dropped to 0.04 L/m^2.min after 1000 minutes with min flux reduction percentage of 15% at 0.8 LPM flow rate. However, the membrane flux for the case of no spacer was denoted as 0.04 L/m^2.min and it decreased noticeably to 0.03 L/m2.min by 25% as a reduction percentage. Whereas, flux reduction percentage of FS without primary settling was 13% with adding spacer and 42% without spacer as it could be seen in Figure 38.

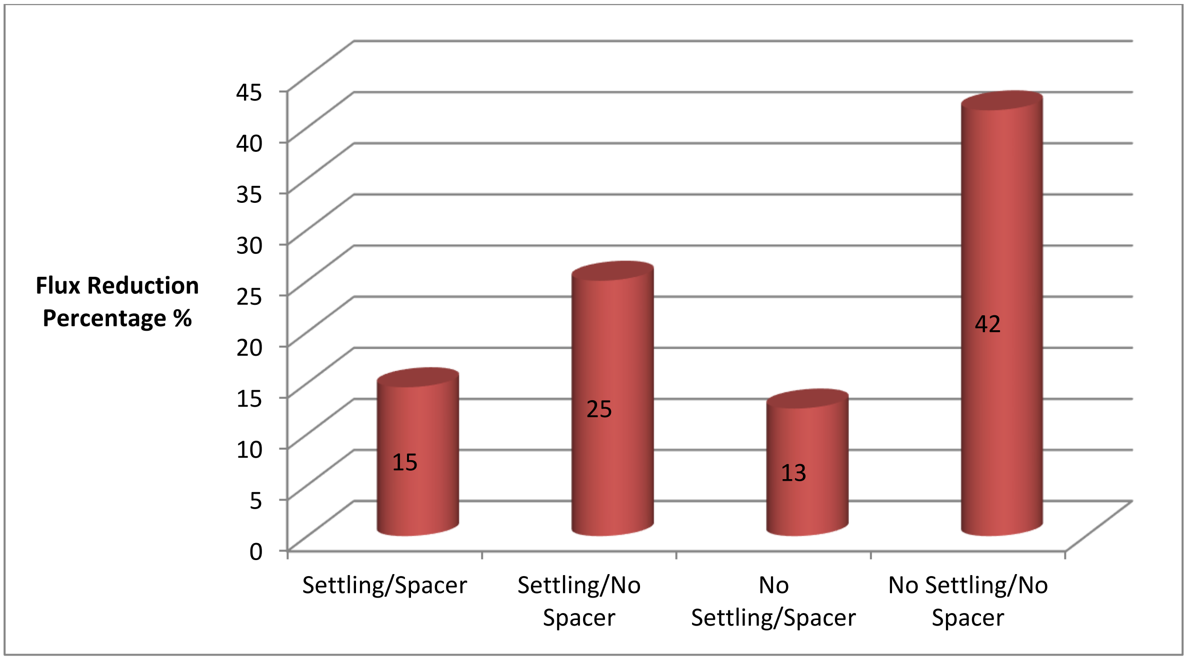

Figure 38: Flux Reduction Percentage before and after Settling, with and without Spacer

The enhancement of membrane flux for the pre-settled construction water due to the removal of settleable solids. The achieved value of turbidity after settling was 26 NTU. Despite the fact that the performance of settling tank varies, an approximation of the removal of suspended solids based on the particle size. Where suspended solids are grouped according to their sizes, in which a particle size would be considered as dissolved if it is less than 0.001 µm. While, the colloidal particles are ranging from (0.01 – 100 µm). On the other hand, particle sizes that are greater than 1000 µm (1mm) would be considered as settleable solids. Moreover, the concentration of TSS would be known as the mass of particles having a diameter over 1 µm and occurring in a recognized volume of water. As a physical aspect, suspended solids could be sectioned further classified into settleable solids, often greater than 100 µm, and nonseattleable suspended solids, that are less than 100 μm . However, it would be difficult to monitor the fine nonsettleable suspended solids and they cause the major problems within the recirculating systems [96].

4.3.2 Effect of Multimedia filtration on Membrane Flux

In order to further investigate the impact of the water quality before being treated by FO unit, multimedia filtration was applied to the dewatering construction water for the sake of lowering turbidity and enhancing the performance of forward osmosis process. Construction water with initial turbidity of 300 NTU was the influent to the multimedia filter. The effluent's turbidity was equal to 24 NTU. The obtained effluent from multimedia filters would be used as a feed solution in the FO channel by adding a spacer on the feed solution side with 0.8 LPM flow rate. Also, in this case, the effect of membrane orientation on flux was evaluated for both when membrane's active layer was facing feed solution (FS-AL) and the active layer was facing draw solution (DS-AL).Furthermore, based on membrane flux, recovery rate and flux reduction percentage a comparison was carried out between filtered, settled and high turbidity construction water feed solutions.

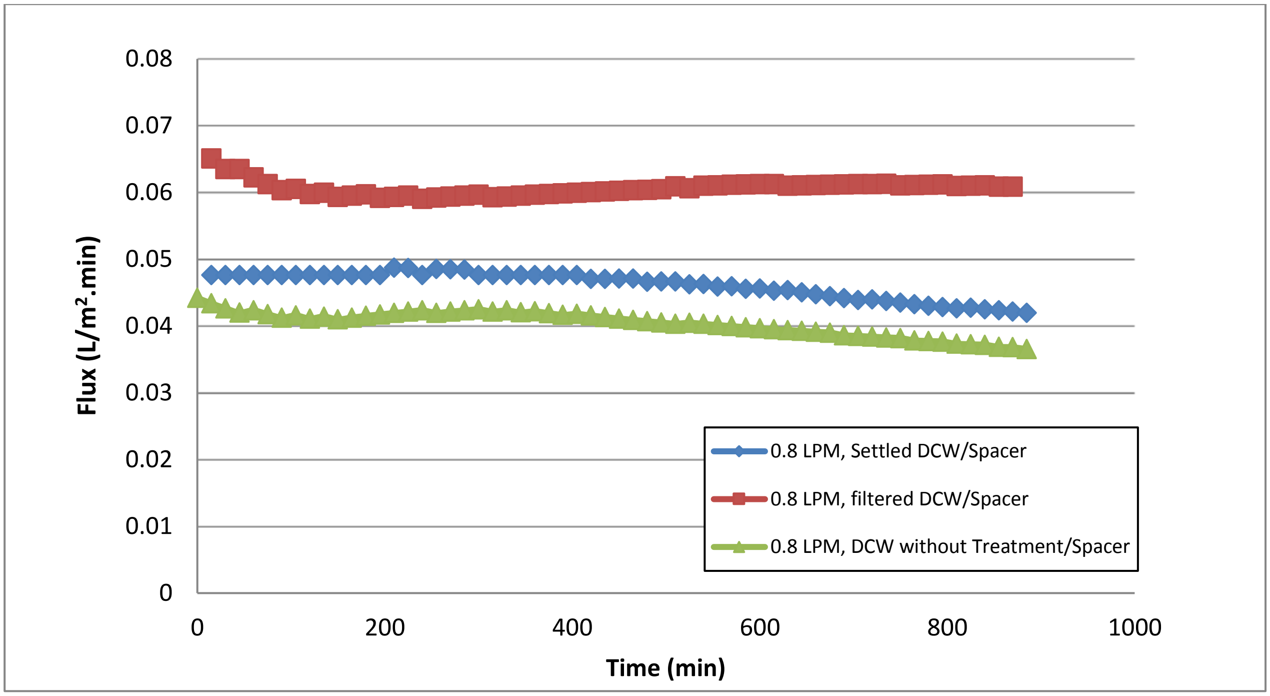

Figure 39: Membrane flux of settled, filtered and DCW without treatment, with spacer in the feed solution side

After running the FO system with filtered construction water feed solution with initial turbidity of 24 NTU under the flow rate of 0.8 LPM in (DS-AL) operation mode. Figure 39 shows that membrane flux of construction water feed solution after using multimedia filtration decreased from 0.08 L/m^2.min to 0.06 L/m^2.min and it stayed constant until the end of the experimental run. After combining this run with different feed solutions of same flow rate with spacer. It could be seen that the best case scenario was when multimedia filter was employed because it gives the highest recovery rate of 30% with low membrane flux reduction of 8% as shown in Figures 40 and 41. Based on previous studies, when the concentration of feed solution changes while maintaining the concentration of the draw solution, the membrane flux noticeably increases with respect to the osmotic pressure difference [97].

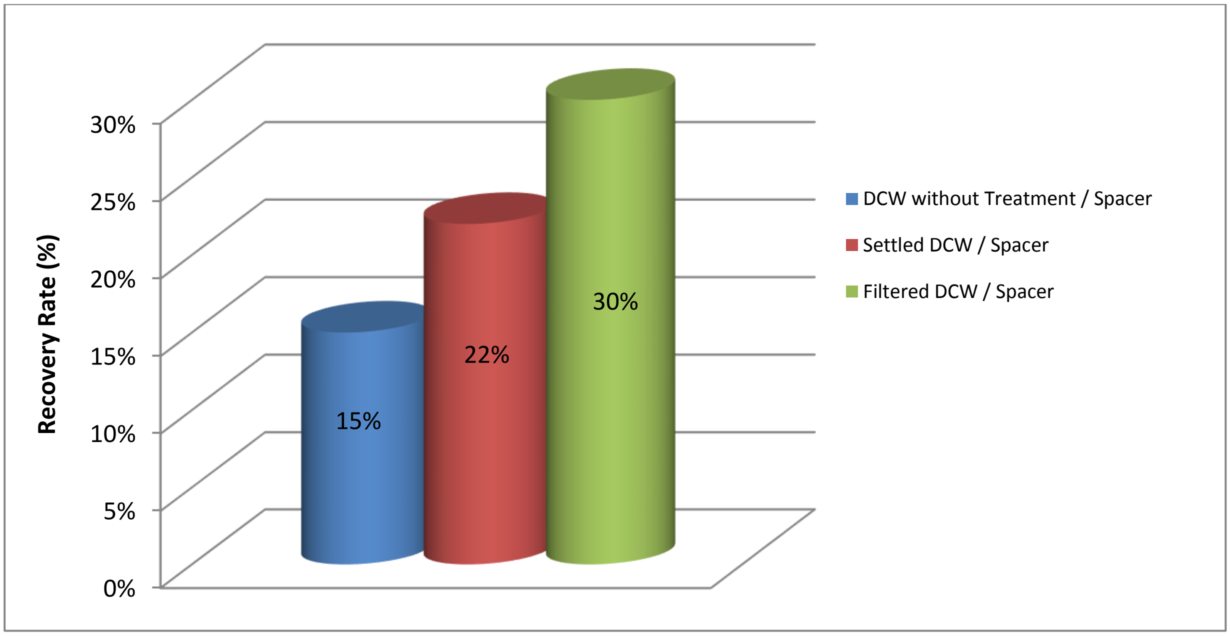

Figure 40: Recovery rate of settled, filtered and DCW without treatment, with spacer in the feed solution side at 0.8 LPM flowrate

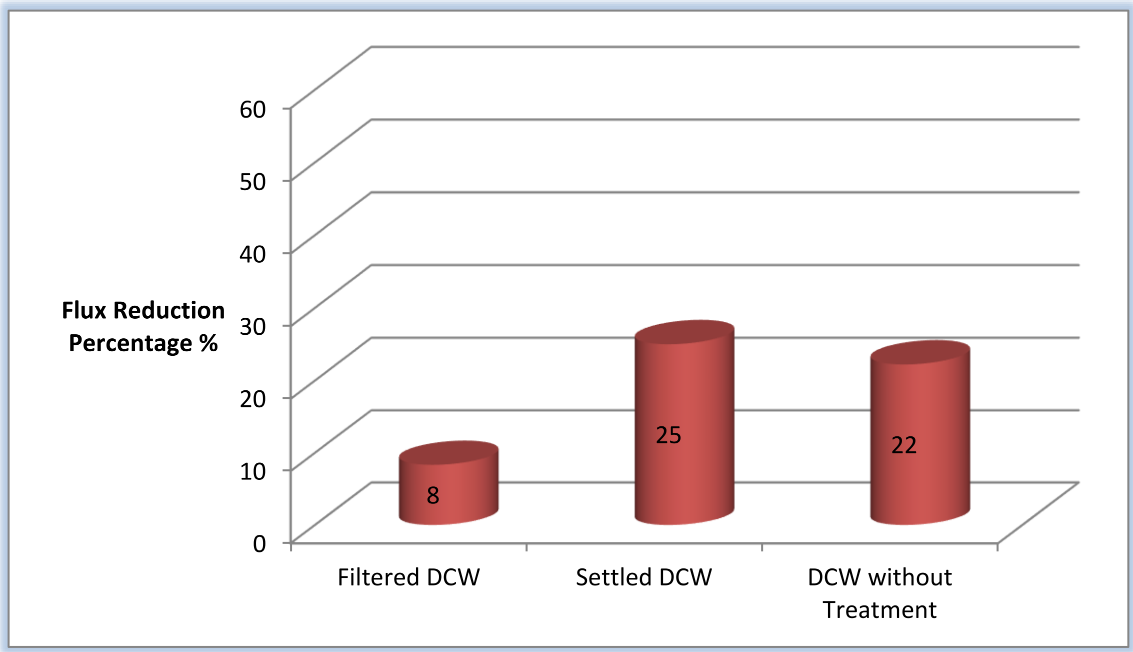

Figure 41: Flux reduction percentage of settled, filtered and DCW without treatment, with spacer in the feed solution side at 208 LPM flowrate

Pretreatment of dewatering construction water by multimedia filtration gave better membrane flux, recovery rate and flux reduction percentage in the FO process compared to pretreatment using settling or no treatment. The suspended solids presented in DCW were trapped in the media filter beds and the effluent from the filtration process was construction water with minimum value of turbidity and suspended solids. Pre-filtration of construction feed water removed most of the suspended solids which were responsible of membrane fouling specially at high flow rate and resulted in more consistent membrane flux. Moreover, the use of spacer with pre-filtered feed solution in (DS-AL) operation mode promoted mixing of feed solution and reduced the concentration polarization at the feed side [84] [98]. As the turbidity level of feed solution was decreased, the membrane flux of settled and pre-filtered feed solution increased irrespective of flow rate. This observation reveals that FO process with spacer was more effective when the construction water pretreated before FO filtration took place.

Membrane fouling caused a noticeable decrease of the recovery rate and would dropped the flux to minimal value. Therefore, the denoted drop of membrane flux was not surprising in this experimental runs. However, compared the flux decline and SEM images with those after using settling and multimedia filter with adding spacer , it can be understood that membrane fouling in FO was much slighter than that in the dewatering construction water without treatment, which indicates a promising application of FO for construction water treatment. Figure 42 shows the differences between both samples of CTA membrane with settled and filtered feed solution, all SEM images were at the same magnification scale.

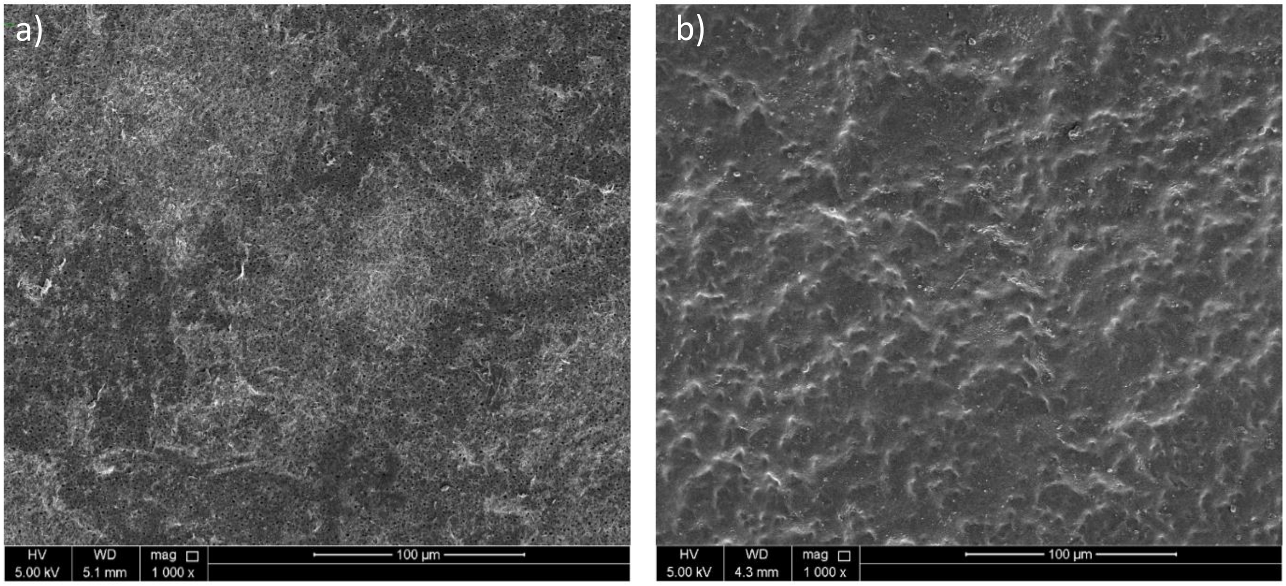

Figure 42: SEM analysis a) 0.8 LPM for Settled DCW with spacer in the feed channel, b) 0.8 LPM for Filtered DCW with spacer in the feed channel

From Figure 42 (a) and (b), it could be seen that the accumulation of the particles on the membrane surface was less when multimedia filter was used compared to settle DCW and these colloidal particles tend to decrease into a smaller size. Hence, better performance of the FO process was achieved with higher membrane flux and less membrane fouling opportunity over the 16 hours of the experimental run.

4.4 Effect of Membrane Orientation

One of the main affecting factors within any FO system is the membrane orientation, due to the asymmetric nature of FO membrane [99]. FO membrane has a dense rejection layer, which is on the porous support layer in order to provide mechanical support to the membrane [100] [101]. This structure lead to two membrane orientation that is unique to FO because of the presence of two different solutions in each side of the membrane. To understand the impact of membrane orientation and its asymmetric design on flux performance under various flow rates, experiments were carried out using 0.5M NaCl draw solution, filtered dewatering construction water feed solution with 0.8 LPM and 2.2 LPM flow rates for both feed and draw solutions.

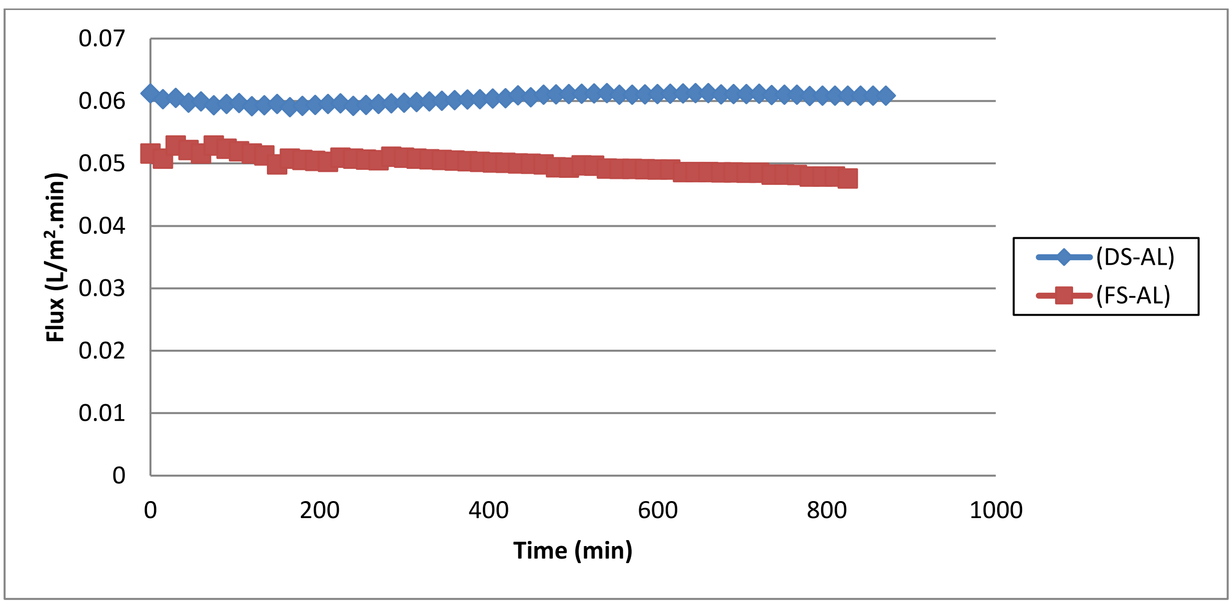

Figure 43: Membrane flux of filtered DCW FS, 0.5 M NaCl DS, when (DS-AL) and (FS-AL) operation modes are used at 0.8 LPM flowrate

It could be seen form Figure 43, that the membrane flux at 0.8 LPM flow rate starts with 0.05 L/m^2.min when the active layer of the membrane was confronting the feed solution (FS-AL) operation mode, while it begins at 0.06 L/m^2.min when the membrane flipped and the active layer of the membrane was confronting the draw solution (DS-AL) operation mode.

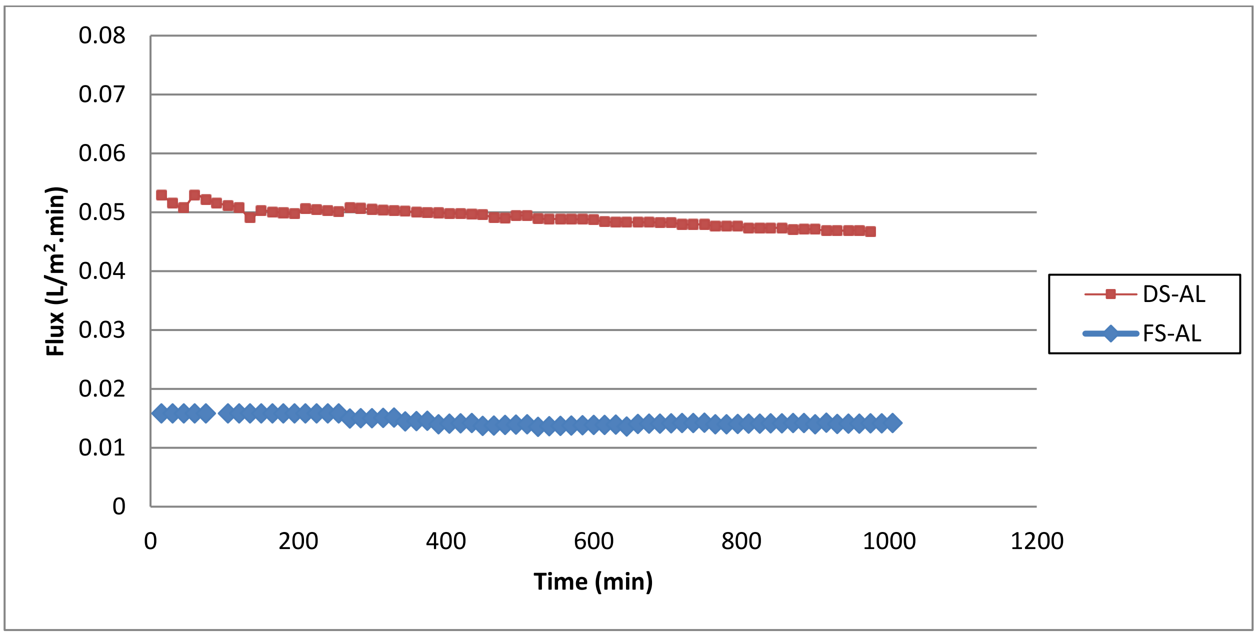

Figure 44: Membrane flux of filtered DCW FS, 0.5 M NaCl DS, when (DS-AL) and (FS-AL) operation modes are used at 2.2 LPM flowrate

On the other hand, for the flow rate of 2.2 LPM for the same samples of feed and draw solutions. It was noticeable as shown in Figure 44, that higher flux was obtained when the membrane faced the draw solution (DS-AL) with an initial value of 0.052 L/m^2.min. While the flux was much lower when the membrane was changed to FS-AL operation mode with an initial value of 0.015 L/m^2.min. The flux drop for these two orientations with the 2.2 LPM flow rate was about 70%. However, the incoming water flux that moves from feed side to the draw side diluted the draw solution at the active layer. If this dilution of the draw solution happens when the (FS-AL) operation mode, then the dilution occurs within the support layer of the membrane and caused what is called dilutive internal concentration polarization (DICP) which affected the membrane flux more severely than when using the other membrane orientation mode (DS-AL) and the phenomena is dilutive external concentration polarization [102] [83] [103]. Figure 45 (a) and (b) below explains why the net osmotic pressure in the (DS-AL) operation mode is more than in the (FS-AL). As it can be seen in (FS-AL) operation mode, there was a noticeable decease in the draw solution osmotic pressure due to the dilution within the support layer by the incoming flux from the feed solution. Similarly, a reduction in the net osmotic pressure has occurred within the active layer due to the concentration increase of the feed solution. On the other hand, for the experiment that has been carried out in (DS-AL) as shown in Figure 45 (b) the net osmotic pressure was higher than in the case of (FS-AL). However, there was a reduction in the osmotic pressure near the active layer due to the dilution by the incoming flux. Moreover, a slight decrease has occurred in the osmotic pressure near the membrane support layer because of feed solution concentration elevation.

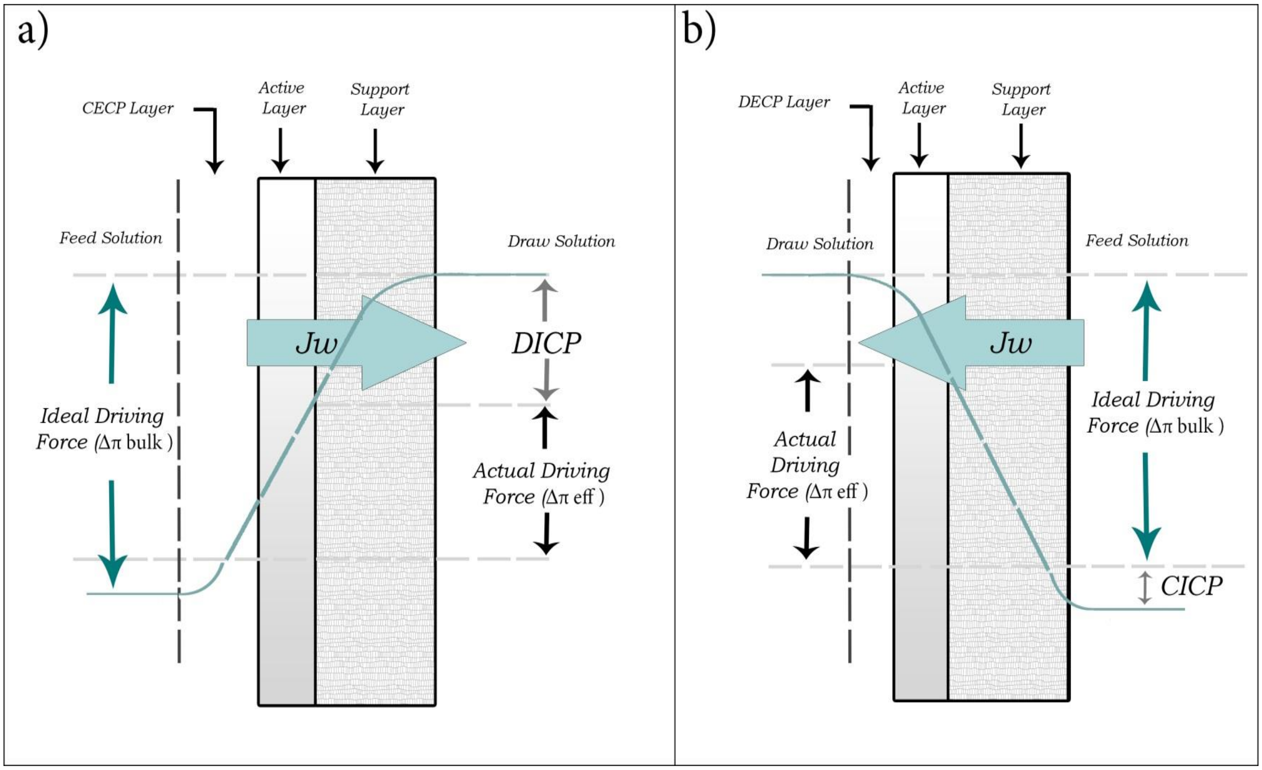

Figure 45: Illustration of the effect of membrane orientation on the net osmotic pressure, a) the membrane active layer is facing the feed solution FS-AL b) the membrane active layer is facing the draw solution DS-AL

Membrane flux would get boosted as well in the case of active layer is facing the draw solution with the phenomena of external concentration polarization (ECP) as in the (DS-AL) operation mode [88] [81] Furthermore, the enhancement of flow rate decreased the membrane flux in hydrodynamic conditions as the flow rate raises in (FS-AL) operation mode.

Results obtained from shown figures 45 (a) and (b) are indicating that when feed solution is placed against the active layer of FO membrane and with previously used flow rates in the presence of spacer. The use of a spacer in the (FS-AL) mode created turbulent flow with the used flow rates and it would lead to interface between DS and the support layer [80]. The turbulent flow would enhance the advection of draw solution to the support layer of membrane. The increase in DS's advection to the inside of the support layer increased the concentration of DS within the support layer. Hence, this would lead to an increase in the osmotic pressure and in the flux in the experimental run at 0.8 LPM flow rate. As water flux comes from feed solution it would dilute the draw solution at the interface between both the active and support layers, this would resulted in a severe DICP. Other supportive studies have shown that increasing the draw solution concentration when (FS-AL) orientation was applied would obtain a sever ICP [84] [104]. This illustrates the reduction in water flux as well as the reduction in the concentration of draw solution at both interfaces of active and support layers. It could be recognized that (FS-AL) operation mode has a relatively low impact on ICP occurrence and increase due to the suspended solids that penetrated across membrane active layer and trapped directly close to the spacer.

In (DS-AL) operation mode, the Flux was higher than in that in (FS-AL) mode but the latter mode maintained more stable flux during the experiment due to low membrane flux. Membrane orientation has been the main reason that led to such differences in the membrane flux. However, in (DS-AL) operation mode only DECP has taken place at the membrane active layer's surface. However, it could be understood that the adverse impact of DICP on the performance of the FO unit was much more than DECP [105] [106] [107]. Moreover, it is approved that the membrane flux was existed as a function of the osmotic pressure difference between both the bulk draw solution and feed solution. Furthermore, during (DS-AL) mode the flux was high which has caused a severe dilution of the draw solution and decreased membrane flux. Based on the computed difference between the two different membrane orientations not only DICP occurred but also the CECP at the active layer in (FS-AL). As a sequence, the initial water flux of 2.2 LPM flow rate in the mode of (FS-AL) was 0.015 L/m^2.min lower than in that of 0.8 LPM in (FS-AL) operation mode which was equal to 0.05 L/m^2.min, in which only DICP took place. Hence, there is a direct proportional between flow rate and DICP, which would reduce the membrane flux. In the same manner, not only DECP occurred but also the CICP at the support and active layer in (DS-AL) operation mode. Accordingly, the initial membrane flux of 2.2 LPM flow rate in the mode of (DS-AL) started at 0.055 L/m^2.min and it was lower than the initial membrane flux for 0.8 LPM flow rate that started at 0.06 L/m^2.min in the same operation mode where only DECP existed. The result show that the adverse impact of the CECP when the FO operating in the (FS-AL) mode was much higher than that of the CICP when FO operating in the (DS-AL) mode. Accordingly, (DS-AL) operation mode is more appropriate for the treatment of the dewatering construction water especially when feed solution was pre-filtered and a spacer was placed on the feed solution side of the membrane.

CHAPTER 4: CONCLUSION AND RECOMMENDATION

In this study dewatering construction water (DCW) was used as a feed solution (FS) and sea water was used as a draw solution (DS). The impact of flow rates of FS and DS, placement of spacer, pretreatment of the feed solution and orientation of the membrane on the membrane flux were investigated. The major conclusions from this study are summarized as follows:

- When the FO is operating in (DS-AL) mode by using 35,000 ppm (0.5M) NaCl draw solution and 6,000 ppm dewatering construction water feed solution and the flow rates were in the range of (0.8-2.9) LPM spacer, it was found that the membrane flux decreased with the decrease of the flow rate of feed solution and draw solution. In this operation condition, the highest membrane flux was obtained at a flow rate of 2.9 LPM. The flux started at 0.13 L/m^2.min and dropped to 0.05 L/m^2.min after 1000 minutes with a recovery rate of 20%. Concentration of suspended solids in the feed solution with high flow rates probably led to both film formation on the surface of the membrane and inorganic scaling. Furthermore, based on the relatively high solute concentration that is present in the draw solution, a higher ECP on the surface of the membrane active layer would be more significant.

- Using higher flow rates with spacer on the support layer of the membrane, there was a high initial flux that would increase the conductive flow through the membrane and increase fouling on the feed side. Also, it can be understood that as the flow rate increases with the use of spacer its recovery rate would decrease as a result of colloidal particles entrapment. Hence, it can be asserted that as flow rate increases with the use of spacer, the recovery rate would increase up to a certain value. Otherwise, with a higher flow rate, like 2.9 LPM a clear decrease will occur as a result of more colloidal particles entrapment. However, the increase of water flux was predicted when spacer was utilized since it was considered that resulting turbulence would mitigate the concentration polarization. Thus, flux would be enhanced.
- The influence of pretreatment of DCW on the performance of the FO process was also investigated. Settled and pre-filtered feed solution was used and the results showed that the recovery rate of the FO process increased the most after pretreatment by multimedia filtration with a recovery rate of 30%. Pre-filtration of construction feed water removed most of colloidal particles which were responsible for membrane fouling at a high flow rate and resulted in a more consistent membrane flux.

- In (FS-AL) operation mode, the adverse effect of CECP was much higher than that of the CICP when FO was operating in the (DS-AL) mode. Accordingly, (DS-AL) operation mode is more appropriate for the treatment of the dewatering construction water especially when feed solution was pre-filtered and a spacer was placed on the feed solution side of the membrane.

It is recommended to use the following operation parameters for the treatment of DCW feed solution by FO unit to obtain the highest membrane flux and highest recovery rate. This can be achieved by using the optimum flow rate of 2.2 LPM after applying filtration to DCW with adding a spacer in the feed solution side.

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LIST OF ABBREVIATIONS

DCW : Dewatering Construction Water

CTA : Cellulose triacetate

CA : Cellulose Acetate

RO : Reverse Osmosis

MSF : Multi-Stage Flashing

FO : Forward Osmosis

SEM : Scanning Electron Microscope

MED : Multi-Effect Distillation

MD : Membrane Distillation

TFC : Thin Film Composite

ED : Electro-Dialysis

TDS : Total Dissolved Solids

TSS : Total Suspended Solids

TS : Total Solids

DS : Draw Solution

FS : Feed Solution

PRO : Pressure Retarded Osmosis

CP : Concentration Polarization

ECP : External Concentration Polarization

CECP : Concentrative External Concentration Polarization

DECP : Dilutive External Concentration Polarization

ICP : Internal Concentration Polarization

CICP : Concentrative Internal Concentration Polarization

DICP : Dilutive Internal Concentration Polarization

DS-AL : Active Layer of the Membrane Facing Draw Solution

FS-AL : Active Layer of the Membrane Facing Feed Solution

LPM : Liter per Minute

LIST OF SYMBOLS

A : Pure water permeability coefficient ($L.m^{-2}.h^{-1}.bar^{-1}$)

B : Salt permeability coefficient ($m.s^{-1}$)

C : Solute concentration (mg/L or Moles or M)

D : Diffusion coefficient (m^2s^{-1})

S : Membrane structure parameter

d_h : Hydraulic diameter (m)

J_W : Membrane flux ($L/m^2.min$)

k : Mass transfer coefficient

K : Resistance of support layer of the membrane to solute diffusion (s/m)

L : Length of the channel (m)

M : Molar concentration of solution (M)

M_W : Molecular weight (mol/g)

n : Van't Hoff factor

P : Applied hydraulic pressure (bar)

R : Universal gas constant (0.0821 $L.atm.mol^{-1}.K^{-1}$)

Sh : Sherwood number

T : Absolute temperature (K)

N_A : Avogadro's number

π : Osmotic pressure (atm or bar)

σ : Reflection coefficient

τ : Tortuosity

ε : Membrane porosity