Desalination of Brackish Water Using Reverse Osmosis

By

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List of Abbreviations

AMTA	American Membrane Technology Associations
AWWA	American Water Works Association
BWRO	Brackish Water Reverse Osmosis
CA	Cellulose Acetate
CIP	Clean In Place
ED	Electro-dialysis
GDP	Gross Domestic Product
MED	Multi Effect Distillation
TVC	Thermal Vapor Compression
MVC	Mechanical Vapor Compression
NDWQS	National Drinking Water Quality Standards
NOM	Natural Organic Matter
RO	Reverse Osmosis
NF	Nano-Filtration

MF	Micro-Filtration
RR	Rate of Recovery
TDS	Total Dissolved Solids
TFC	Thin Film Composite
UNDP	United Nations Development Program
NaCl	Sodium Chloride
$MgCl_2$	Magnesium Chloride
UF	Ultra-Filtration
CF	Cartridge Filter
D.S	Draw Solution
F.S	Feed Solution
F.O	Forward Osmosis
MSF	Multi-Stage Flash
SDI	Silt Density Index
CTA	Cellulose Tri-acetate

Abstract

Pakistan is among the 36 most water stressed countries and facing water scarcity problem. Desalination of brackish water using reverse osmosis is a common practice now a days adopted for fresh water supply. In reverse osmosis, the sustainability of the process is mainly based on pre-treatment and its membrane performance.

This study aims to compare at pilot scale the rejection efficiency of RO membranes with different pretreatment options at different transmembrane pressures and TDS conditions. In this study, synthetic brackish water was prepared and performance evaluation was carried out using brackish water reverse osmosis (BWRO) membranes preceded by different pre-treatment technologies including 5 and 1 µm cartridge filters, Ultra-filtration (UF) having 0.02 µm pore size, and forward osmosis (FO) using 0.25 M NaCl and $MgCl_2$ as draw solution (DS) to avoid membrane fouling and improve process performance. Two commercial membranes, Filmtec Lc-Le-4040 and Hydranautics-CPA5-LD-4040 were also compared in parallel.

Our results revealed that cellulose tri-acetate forward osmosis membrane preceded by polyamide filmtech lc-le-400 membrane with 0.25 M $MgCl_2$ used as a draw solution gave overall 97% rejection with less fouling characteristics. Ultra-filtration (UF) membrane preceded by both filmtech lc-le-4040 and hydranautics cpa5-ld-4040 membrane also found effective and gave 98 and 96% rejection but having fouling potential to UF membrane due to high pressure application and for RO membrane due to presence of other ionic compounds. 5 & 1 µm melt blown cartridge filter prior to RO membrane also showed effective results with both membrane

Chapter 1

Introduction

1.1. Background

Due to increase in population, commercial and industrial activities, access to clean and safe drinking water has become a global issue over the past few decades. Fresh water resources for drinking and domestic use are continue to decline (Shannon et al., 2008). Pakistan is among the 36 most water stressed countries mainly because of prolonged droughts and lack of implementation of efficient treatment technologies (Reig, et al., 2013). Water scarcity is the imbalances between availability and demand. The demand of water is increasing day by day due to the improvement of living standards with time and urbanization, these imbalances are prominent in Pakistan. Access to safe drinking water is the right of every person but about 60% Pakistanis are deprived of this basic necessity of life.

Major part of the world's water is seawater, brackish water and groundwater. Approximately, 97.4% of the entire water available on earth is salty and 1.984% is located in the ice caps and glaciers, while 0.592% is located as groundwater and only 0.014% of the earth's water is available as fresh water (Kalogirou et al., 2008)

In addition, many dry and arid areas around the world do not have fresh water resources such as rivers, lakes, etc. Therefore, seawater and brackish water have become alternative resources for drinking water.

Brackish water can be defined as the water having TDS in the range of 1000 – 10000 mg/L is considered as brackish water, while the sea water contains TDS in the range of 10000 – 60000 mg/L. The major solutions to water scarcity include water conservation, rainwater harvesting, educating people and reclamation and reuse (UNDP, 2006). In reclamation and reuse desalination is the most efficient and commonly used method throughout the world.

Desalination of water is one of the technology that have been introduced to remove salt and other minerals from saline water to make it suitable for human and industrial consumption. With the increase in water demand, the need for desalination has also increased over the past years, both domestically and commercially (Dadaha et al., 2014).

Treatment of brackish water using desalination is an effective option to overcome clean water scarcity in Pakistan. There are two main processes for desalination, thermal process and membrane process (Dadaha et al., 2014). In membrane process reverse osmosis is the current water treatment technology that has gained world-wide acceptance and over the years remarkable advances have been made in RO technology (Younos et al., 2009). However, as far as Pakistan is concerned the status of desalination is insufficient

1.2. Objectives

- Design and install reverse osmosis plant at NUST (Pilot-Scale)
- Compare the productivity of two commercial RO membranes (i.e. Filmtech Lc Le-4040 and Hydranautics CPA5-LD-4040)
- Optimize membrane performance using an effective pre-treatment (i.e. Forward Osmosis, 5 & 1 µm Cartridge Filters and Ultra-filtration)

1.3. Scope of Study

1. Established automated Reverse Osmosis (RO) Pilot-scale Plant with two parallel RO membrane assemblies having processing capacity 10 L/mint with a post treatment mechanism for mineralization.
2. Optimized RO membrane operation
3. Integration of Forward Osmosis (FO) as a pretreatment with Reverse Osmosis membrane as a less fouling pretreatment option.

Chapter 2

Literature Review

2.1.Desalination

To address the undeniable basic need of pure water, various treatment technologies have been suggested and applied. These technologies are commonly fall into primary (screening, filtration, centrifugation, separation, sedimentation, coagulation and flocculation); secondary (aerobic and anaerobic treatments); and tertiary (distillation, crystallization, evaporation, solvent extraction, oxidation, precipitation, ion exchange, reverse osmosis (RO), nano-filtration (NF), ultra-filtration (UF), microfiltration (MF), adsorption, electrolysis and electro-dialysis) level. However, most of these technologies are not capable of fixing water pollutants in an effective way.

Some methods are energy and operationally intensive and thus are not affordable on a commercial scale. Adsorption techniques are easy and simple but cannot desalinate salty water. In this respect, membrane technologies have got some attention because of their interesting inherent features.

Membranes do not need chemical additives, thermal inputs and spent media regeneration making them more popular over other water treatment technologies. In fact, the advent of membrane technologies have given immeasurable facilities and opportunities to purify water even at the ionic levels. Membrane filtration allows water solvent but reject solute particles present in the polluted water (AWWA, 1999). Currently, several membrane separation techniques such as RO, NF, UF, MF, dialysis and electro-dialysis are available. Among them, RO, NF, UF and MF are pressure driven membrane processes which are frequently applied in water treatment plants.

However, like other membrane technologies, RO also needs the input of high-pressure and consequent energy. Energy consumption costs approximately one half of the total cost in the RO operation. This energy requirement has significantly dampened the popularity of the pressure driven membrane technologies at commercial level. Furthermore, pollutant precipitation reduces the life of membranes module and causes fouling and pore blocking. Some recently invented membranes such as forward osmosis (FO), membrane distillation (MD), and capacitive deionization (CDI) are promising in desalination but are not commercially available.

There are three basic approaches for the separation of water from salt (Dadaha et al., 2014). The first is the thermal approach which result in the phase change of the water and convert into vapors and separate from the residual salt solution and recover the thermal energy for the pre-heating purpose and reuse. Distillation process was the first desalination processes that was commercially used and account for a large portion of desalination capacity of the world. It operate at continuous decreasing pressure condition due to which evaporation is achieved at lower temperature condition. The second approach for the desalination is a membrane based approach. Membrane process are of two types, in the first one, water passes through a semi-permeable membrane that allows the water and blocked the salt content (i.e. MF, UF, NF, RO & FO). While in the second process, ions in solution move toward the anion and cation selective membranes in response to an electric field (i.e. ED) (Karaghouli et.al, 2013). The third is the chemical approaches for the desalination. This approach is very much different from the other two, it includes process such as ion exchange, liquid-liquid extraction, gas hydrate and some other precipitation schemes. In general, it is found that chemical methods are too expensive to apply for the production of fresh water.

2.2.Thermal Process

2.2.1. Multi-Stage Flash (MSF)

Multi-stage flash (MSF) is a type of thermal desalination process in which the brackish or sea water is heated by using fossil fuel and converts into vapors; these vapors are then condensed and separated (Mutaz et al., 2004; Darwish et al., 1991). The latent heat of the vapors are used for the pre-heating purpose of incoming feed. The multi-stage flash operate at continuous decline pressure, resulting in higher permeate. The problem associated with the process is the scaling material deposition on the heat transfer tubes. The process is widely used in the Middle East and are coupled with the power generation plant for the efficient utilization of fuel energy. Burning of fuel resulting the high temperature steam which are used for the production of electricity and after that the low temperature and pressure stream is used to drive the desalination process

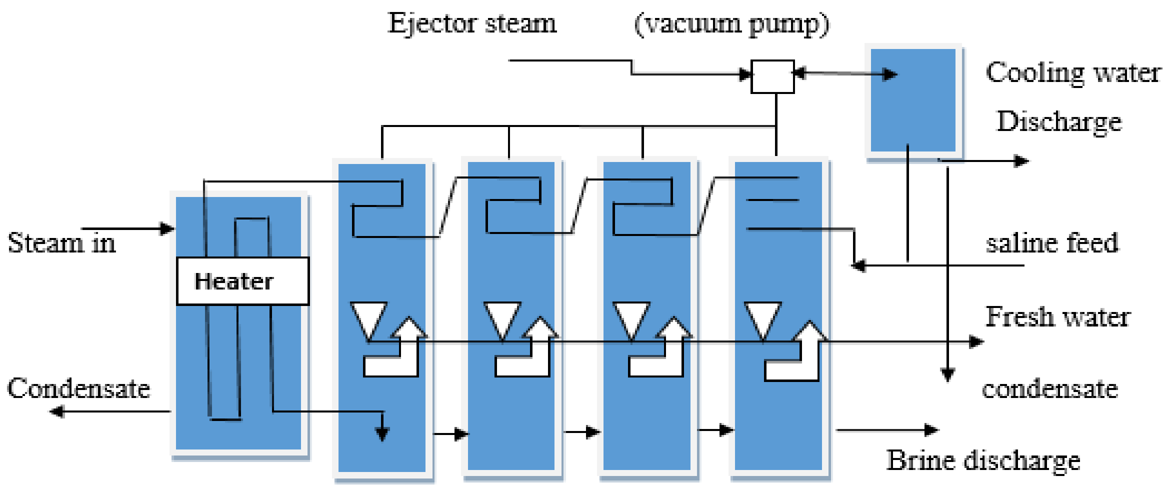

Figure 2.1: Multi-Stage Flash (Adopted from Karaghouli et al. 2013)

2.2.2 Multi-Effect Distillation

Multi-effect distillation (MED) is a type of thermal desalination process like multi-stage flash (MSF) and was establish in the 1950s. Due to scaling problem in the heat transfer tubes MED was replaced with MSF and also it is not in use now a days (Buros et al., 2000). The process have got the attention due to its heat transfer rate. It operates at continuously decreasing pressure condition which result in the evaporation at both higher and lower temperature. The lower temperature value ranges up to 55 ^{0}C. Which result in the efficient utilization of heat from fossil fuel and low temperature steam

MED process may have different arrangement of tube and direction of flow. MED can also be combined with other heating process which result the higher gain output ratio

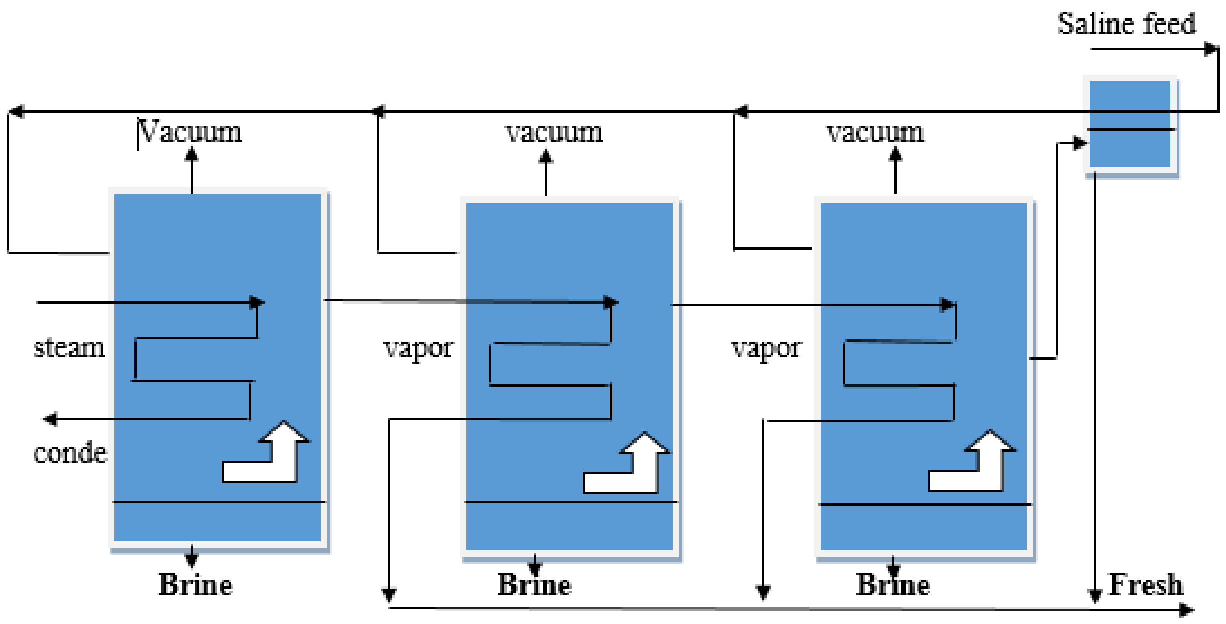

Figure 2.2: Multi-Effect Distillation (Adopted from Karaghouli et al. 2013)

2.2.3. Vapor Compression (Thermal and Mechanical):

Vapor compression processes are based on induced pressure operation. In vapor compression heat is provided by the compression of vapor by mechanical compressor (mechanical vapor compressor (MVC)) or by thermal ejector (thermal vapor compression (TVC)). Vapor compression processes are very useful for small and medium installations. MVC unit ranges up to 3,000 m^3/day while TVC units may range up to 30,000 m^3/day (Miller et al., 2003). The thermal vapor compression have several stages while the mechanical vapor compression has single stage, which results in the MVC having the same specific power (i.e. power per unit mass of water) while the efficiency of TVC increases as the number of stages increase.

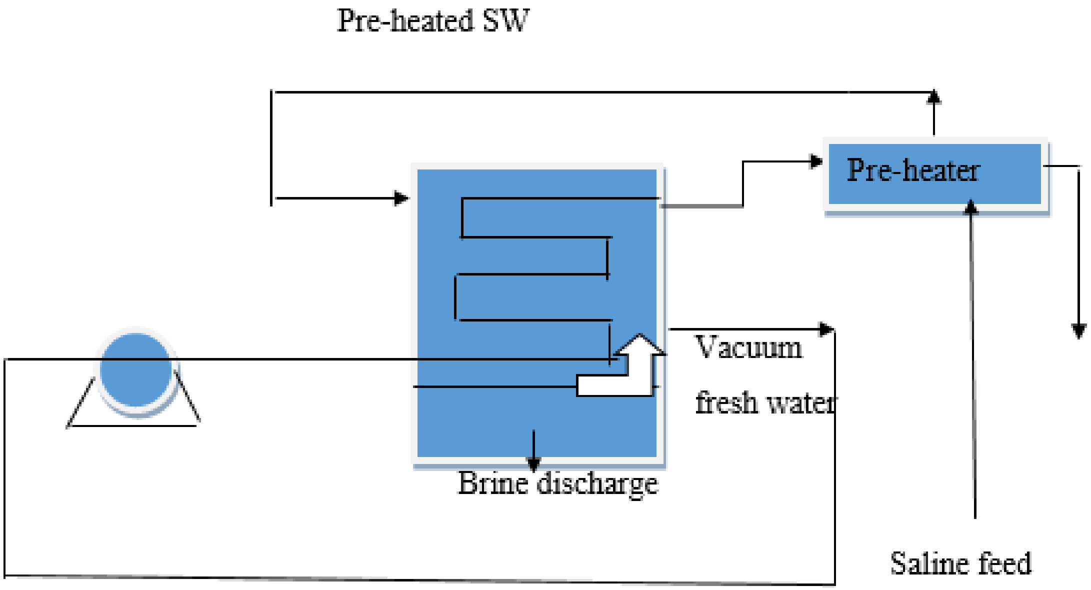

Figure 2.3: Thermal/Mechanical Vapor Compression (Adopted from Karaghouli et al. 2013)

2.3. Membrane Processes

A membrane is a thin film of porous material that allows water molecules but prevents the passage of larger and undesirable molecules such as bacteria, viruses, metals, and salts (AWWA, 1999). Unlike conventional treatment technologies, the membrane technologies was found to be more cost effective and give better quality by removing the particle having size greater than the pore size of the membrane and give low silt density index (SDI) value, which make them more attractive treatment technology for the water having high total dissolve solids (TDS) (Ag et al., 20122; Misdan et al., 2012; Greenlee et al., 2009; Shaffer., 2012; Heijman 2009). Membranes can be made from a wide variety of materials which include polymeric and non-polymeric. The polymeric materials include nylon, acetate, and cellulose, and the non- polymeric materials are metal, ceramics and composites.

2.3.1. Electro-dialysis

Electro-dialysis (ED) uses a current source and flow channels for the separation of water and dissolved salts. In this process the driving force is an electric field and the process is capable of removing ionic components from solution. The feed water is introduced into the channel and then an electric field is applied which will resulting the movement of ions toward the opposite charged plate, which reduce the ionic concentration of water.

A single membrane stack may comprise of hundreds of these alternate channels. In general Electro-dialysis is limited to brackish water having dissolved solids only up to few thousand ppm, because the amount of energy needed for the separation of ions from the solution increases with concentration. ED also requires some pretreatment of the feed water because the membrane of ED is subject to fouling. The cleaning of the membrane in electro-dialysis process to remove the fouling material is achieved by reversing the polarity of the plates several times in an hour that will result in switching the brine channels to freshwater channels, and the freshwater channels to brine channels, and breaks up and flushes out deposits.

2.3.2. Forward Osmosis (FO)

Forward Osmosis is a physical process that uses osmosis phenomena for the production of fresh water. Osmosis is a natural process which involves the impulsive passage of water through a semi-permeable membrane. Forward Osmosis membrane is a dense, semipermeable and highly selective membrane, which allows only water molecules to pass through it and retain all the suspended solids and ions, making it preferred to other filtration membrane (Jin et al., 2012; Hancock et al., 2012). Instead of high pressure force, driving force in forward osmosis is the osmotic force which is induced by the difference in potential gradient between the feed water and the draw solution. This make FO energy efficient and green technology (Cath et al., 2006; Yen et al., 2010; Qin et al., 2010; Tang et al., 2014)

If a vessel is filled with two fluids; fresh water and brine water separated by a semi-permeable membrane, water diffuses through membrane from the less concentrated side towards the greater side due to concentration difference. As fresh water passes from the membrane the levels of the two solutions become uneven creating a pressure difference that ultimately brings the passage to a stop. This pressure difference is known as osmotic pressure.

This osmotic phenomena can be reversed by applying the pressure greater than the osmotic pressure. The osmotic pressure does not only stops the osmosis but forces it to reverse which is known as reverse osmosis.

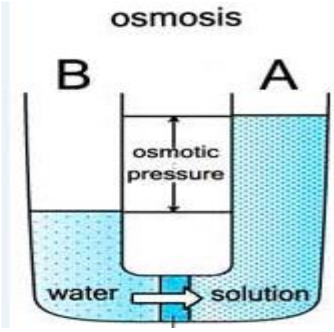

Figure 2.4: Forward Osmosis

2.3.3. Reverse Osmosis (RO)

Reverse Osmosis is a pressure-driven process whereby a semi-permeable membrane rejects dissolved constituents present in feed water, allowing fresh water to pass through. The permeate flows through the membrane by the pressure difference created between the pressurized feed-water and the product-water (which is nearly atmospheric pressure). The remaining feed (concentrate) continues through the pressurized side of the reactor as brine. No heating or phase change occur.

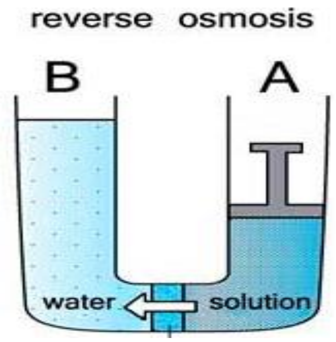

Figure 2.5: Reverse Osmosis

The RO process can be used to desalinate both brackish water and sea water and is effective for removing total dissolved solids (TDS) concentrations of up to 45,000 mg/L (Younos et. al, 2009). It removes all the organic molecules, viruses, multivalent as well as monovalent ions present in water which makes this process highly effective. Salinity removal is usually greater than 99%

2.4. Types of Membrane

There are two types of membranes which commonly used for desalination in RO process.

- Cellulose Acetate Membranes
- Non-Cellulose Acetate membranes (Thin film composite membranes)

Membrane choice depends on the nature of feed-water and it is essential to use the most suitable one according to feed characteristics.

i) Cellulose Acetate Membranes

Cellulose acetate (CA) membranes are made from acetylated cellulose. Fouling resistant due to smoothness of the surface. Relatively it is easy to make and have good mechanical strength. Cellulose acetate membranes have higher flux and thus require lesser area, are relatively resistant to small concentrations of chlorine (up to 5ppm), and can be kept free of bacteria.

Cellulose acetate membranes also possess certain shortcomings. It tends to hydrolyze over time, which reduce their selectivity. Also, they are very sensitive to change in pH. As temperature increases the salt rejection of CA membranes decreases. Therefore, feed temperature typically should not exceed 35°C.

ii) Non-CA membranes

Cellulose acetate membranes were the prevailing choice for RO membranes before the arrival of thin film composite (TFC) RO membranes. Thin film composite membranes are chemically and structurally heterogeneous. Mostly, TFC membranes are manufactured with a porous and highly permeable support such as poly-sulfone, coated by aromatic polyamide thin film. The thin film is the salt rejecting layer where the two base layers provide a porous structure whose primary function is strength.

These membranes have a higher flux rate, high filtration rate, good mechanical strength, and allow high rejection of unwanted materials like salts (US EPA, 2005). Along with that, TFC membranes also offers some other advantages over CA membranes, it can reject some low molecular weight organics. Also flexible over a wide range of pH (2-11) and temperatures (45^o) as compared to CA.

TFC membranes are sensitive to chlorine and can be highly susceptible to attack by chlorine which resulting the drastic decrease in salt rejection. Most TFC membranes can only tolerate up to 1000 mg/L-hrs. of chlorine exposure which is far less than CA membrane tolerance. Some additional pre-treatment must be performed before feed is exposed to polyamide TFC membrane.

2.5. Modules of Membrane

Mainly there are four types of modules.

i. **Spiral wound:** It is the most common module used for nano-filtration and reverse osmosis (Sagle and Freeman, 2004). In this module the perforated permeate collection tube is wrapped by a flat sheet membrane (Baker, 2004). The feed flows through the one side of the membrane and permeate is collected on other side and spirals in towards the collection tube.

ii. **Tubular**: In this modules, the feed solution is pumped into the tube and the membrane is placed inside the tube.

iii. **Capillary (Hollow) Fiber:** It consist on bundles of hollow fibers placed in pressure vessel and used for sea water desalination.

iv. **Plate and Frame:** The plate-and-frame module is the simplest structure, consist of two end plates, flat membrane sheet, and spacers

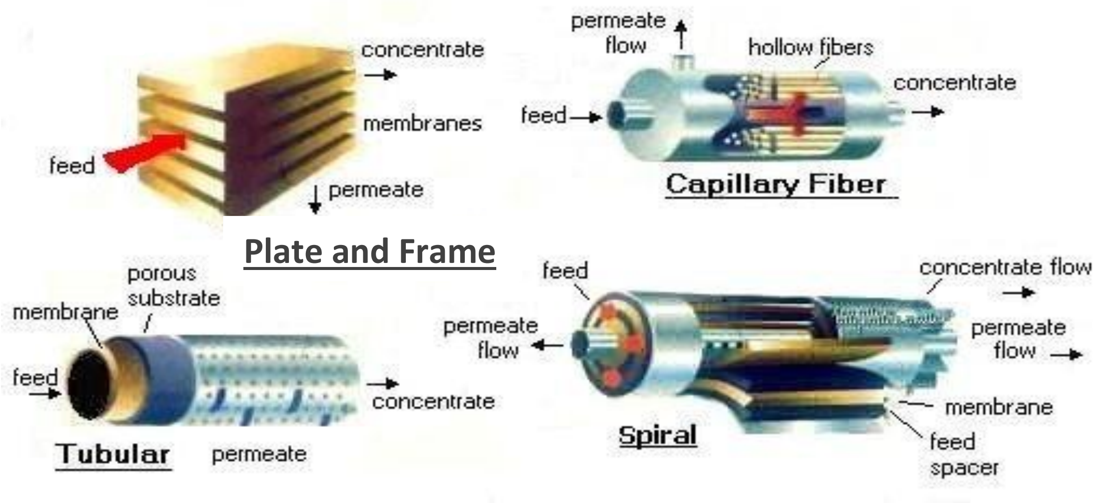

Figure 2.6: Types of membrane module

2.6. Membrane Fouling

Feed water may contain a high amount of suspended and dissolved solid which accumulate on the surface of membrane in case of membrane process and on the surface of heat transfer tube if thermal process are used and cause fouling, which may result the blockage of the membrane and reducing the heat transfer rate respectively.

Due to these depositions in membrane process, a high amount of pressure is required for the separation, which may cause damage or rupture of membrane and also consume a high amount of energy. Based upon the types of foulant present in the feed-water, fouling can be divided into three main categories:

- **Particulate Fouling**: It can be caused by accumulation of large particles on the surface of the membranes and deposition of smaller particles within the membrane pores.
- **Organic Fouling:** It is believed to be caused by Natural Organic Matter (NOM) in the feed-water.
- **Bio-fouling:** It stems from aquatic organisms, such as algae (Kwon, et al., 2005).

  Moreover bacterial fouling can be caused by: transport of the organisms to the surface, attachment to the substratum, and growth at the surface.

2.7. Pre-treatment Technologies

Selection of the pre-treatment technology depend on the quality of feed-water and types of foulants present. The pre-treatment avoid the depositions of fouling material and provide a uniform quality of product at low operation cost. SDI (Silt Density Index) is a measurement of the fouling potential of suspended solids. The SDI test is used to predict the particulate fouling on the membrane surface In order to protect the RO membranes and minimize their cleaning frequency, selection of an effective pretreatment is a crucial step.

i) Conventional Pretreatment

The conventional pretreatment processes typically consist of screening, chemical addition (coagulation and chlorination), a single- or double-stage sand filtration followed by cartridge filtration. Feed water goes through these stages to produce variable qualities of water.

ii) Membrane Pretreatment (UF/MF)

UF and MF membranes work on a surface removal mechanism, and resemble to a fine screen or sieve. The membrane surface has uniform pore size, which allow the passage of molecules having size lesser than the pore and the particles having size larger than the pore are rejected by the membrane surface, which result the formation of concentrate on the feed side, called as brine. UF can remove the finest particles and have an approximate pore size of 0.01-0.02 microns. MF/UF membranes can be developed from inorganic ceramic material or from polymers and are available in varieties with their respective advantages.

2.8. Post Treatment

Post-treatment of RO cover the pH and permeate ion content adjustment to follow drinking water quality standards and make it useful for portable purpose. Selection and sequence of treatment operations are based on regulatory requirements, permeate quality and design of the system. Post-treatment typically includes, disinfection, stabilization, and corrosion control. The process may include air stripping and degasification process, if CO_2 and H_2S present in the permeate

2.9. Energy Consumption

Reverse Osmosis, being a membrane treatment system, offers the advantage of being a low energy consuming process as compared to other treatment systems. Energy consumption has a direct relation with the feed salinity and recovery rate. Higher salinity feed resulting high electrical energy consumption.

Therefore, energy required to desalinate brackish water is less than the amount which is required for sea water desalination. Around 1.5 – 2.5 kwh/m^3 energy is required to desalinate brackish water, which is much lesser than the other treatment process.

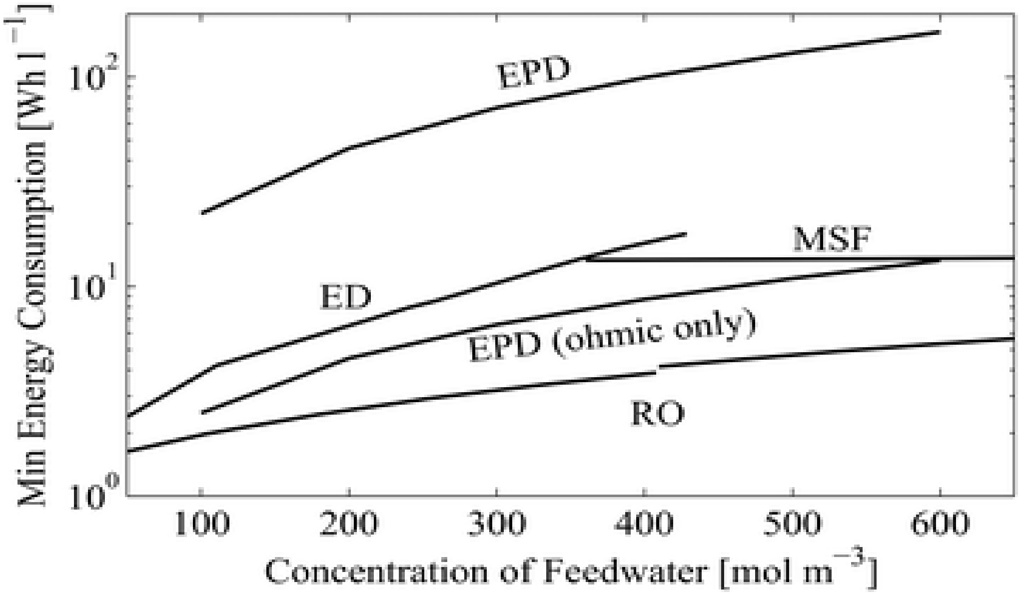

Figure 2.7: Energy Consumption

2.10. Advancement in RO

In order to make water production costs lesser, the process more environmentally friendly, and to overcome the problem of fossil fuels, utilization of renewable energy is becoming widespread, solar energy being the most widely applicable option due to its abundance. Harnessing the abundant energy of the sun makes it possible to supply the power needed to run the desalination plants. Use of solar energy as an electrical input reduces usage of conventional energy and its dependence.

Chapter 3

Material and Methods

3.1.System Configuration

A pilot scale hybrid unit was designed to perform various experiments to check the effectiveness of the process in combination with different pretreatment technologies to make process performance more effective and sustainable. The general layout of the pilot scale plant showing all equipment has been shown in Fig. 3.1. While the actual picture of the system is depicted in Fig.3.2. A pilot scale reverse osmosis unit consist of a feed tank, high pressure feed pump, clean in place (CIP) tank, dosing tank, clean in place pump and dosing pump along with membrane modules consist of two spiral wound RO membrane (4 inch diameter and 40 inch length) in combination with different pretreatment technologies comprising of 5 & 1 µm cartridge filter (CF), 0.02 µm pore size ultra-filtration (UF) membrane and a cellulose tri-acetate (CTA) forward osmosis (FO) membrane was installed at NUST, Islamabad, Pakistan. Permeate and feed flow rate was measured by using rotameter and recycled to the feed tank to make operation continuous, membrane inlet and outlet pressure was measured using bourdon gage (model: 233.55, all stainless steel construction) which was under the permissible limit recommended by the membrane manufacturers (Table 2).

3.2.Synthetic feed preparation

Synthetic feed was prepared for the experiment in accordance to the feed water quality found in the substantial areas of Pakistan (Table 3). Experiments on a pilot scale RO plant using actual brackish ground water were not feasible due to certain constrains such as distance of the site from the plant and transportation of such quantity of brackish water on regular basis.

Synthetic feed preparation include

- De-ionization of ground water
- Addition of salts to make different TDS conditions ranging from 3500 – 4500 mg/L
- Addidtion of 2 mg/L sodium metabisulphite to neutralize free chlorine, to prevent membrane from oxidation.

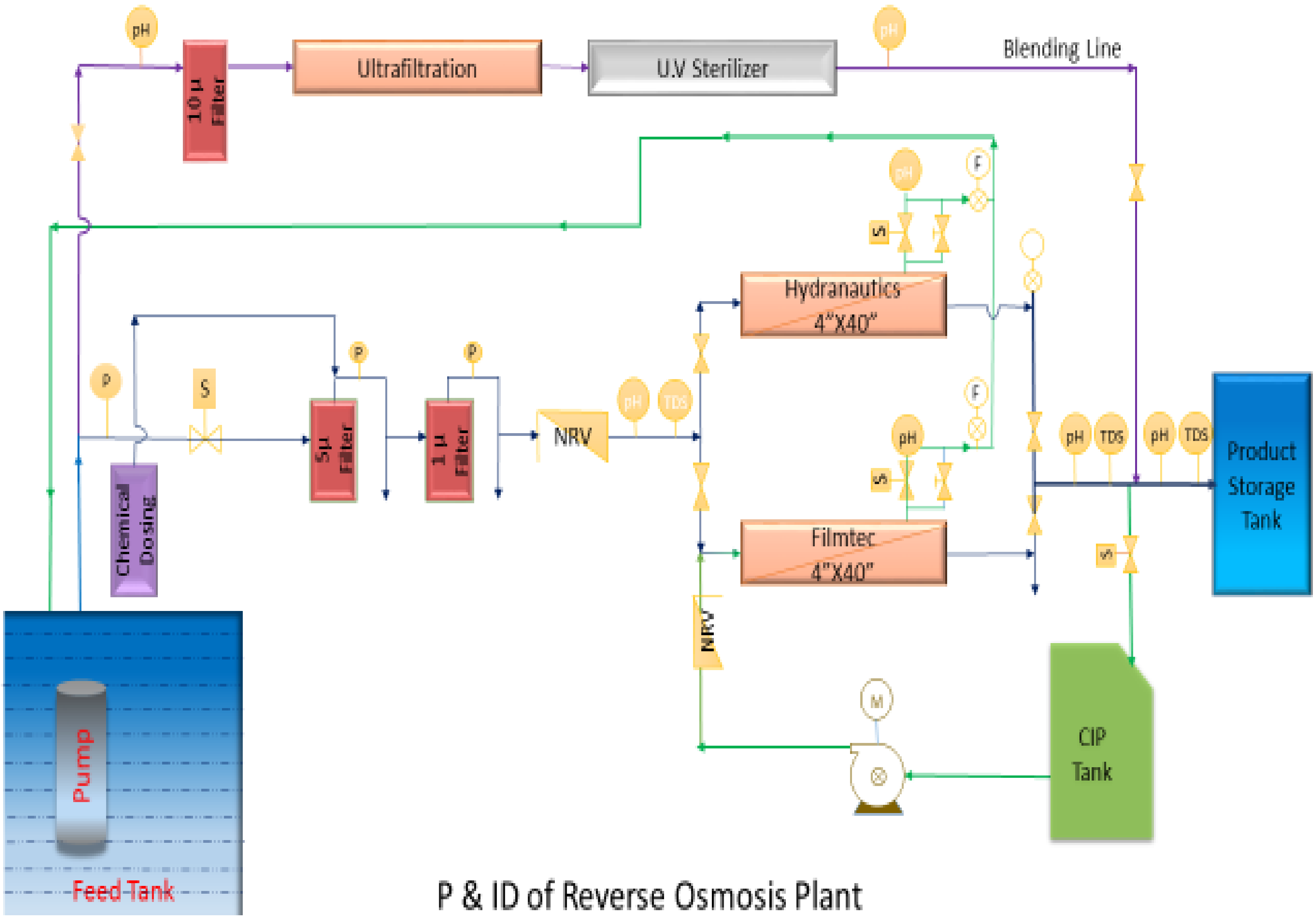

Figure 3.1: Piping and Instrumentation diagram of Pilot-Scale Reverse Osmosis

Figure 3.2: Pilot-Scale Reverse Osmosis Plant

Table 1. List of equipment's.

Description	**Quantity**	**Make/Model**	**Details/Specification**
RO Treatment			
Positive Displacement Pump	1	AA Borehole	4" diameter "AA" borehole submersible pump with 2.2 KW motor
Dosing Pump	1	DLX MA/MB	Microcontroller dosing pump
Clean-in-Place Pump	1	MSP 230, March May, UK	
RO Module	2	Filmtec LCLE-4040 Hydranautics CPA5-LD-4040	See Table 2
Cartridge Filter 1	1	Melt Blown	Pore size: 5 micron
Cartridge Filter 2	1	Melt Blown	Pore size: 1 micron
Tank for feedwater storage	1	Super Tuff	200-gallon capacity, polypropylene
Tank for permeate storage	1	Super Tuff	200-gallon capacity, polypropylene
CIP Tank	1	Locally manufactured	80-liter capacity, polypropylene
Dosing Tank	1	Locally manufactured	80-liter capacity, polypropylene
		Post Treatment	
UF Module	1	-	-
Cartridge Filter	1	-	Pore size: 10 micron
UV Sterilizer	1	Wonder UV E-120	-
Pressure Gauge	8	Bourdon Tube Pressure Gauge	-
Flowmeter	4	-	Panel mounted flowmeter

Table 2. Membrane specifications

Membrane	**Model**	**Avg. permeate flow (m^3/d)**	**Max. feed flow (m^3/h)**	**Max. operating pressure (psig)**	**Membrane filtration area (m^2)**	**Maximum operating temperature**	**PH range**
Hydranautics	CPA5-LD-4040	7.95	3.6	600	7.43	45°C	2 - 11
Filmtec	LCLE-4040	9.5	3.6	600	8.7	45°C	2 – 11

Table 3 Synthetic feed water composition

Component	*Amount (mg/L)*	*Amount (mg/L)*	*Amount (mg/L)*
$NaCl$	889	1016	1169
$CaCl_2$	941	1076	1241
$MgCl_2. 6H_2O$	983	1124	1293
$NaNO_3$	45	52.4	60.3
$NaSO_4$	617	705	811
$NaHCO_3$	18	21	24.6

3.3.Experiments

The synthetic feed was fed to the RO membrane preceded by different pretreatment technologies including 5 & 1 micrometer melt blown cartridge filter, 0.02 micrometer ultra-filtration membrane and forward osmosis membrane to check process performance and found an effective pre-treatment option.

Process Description

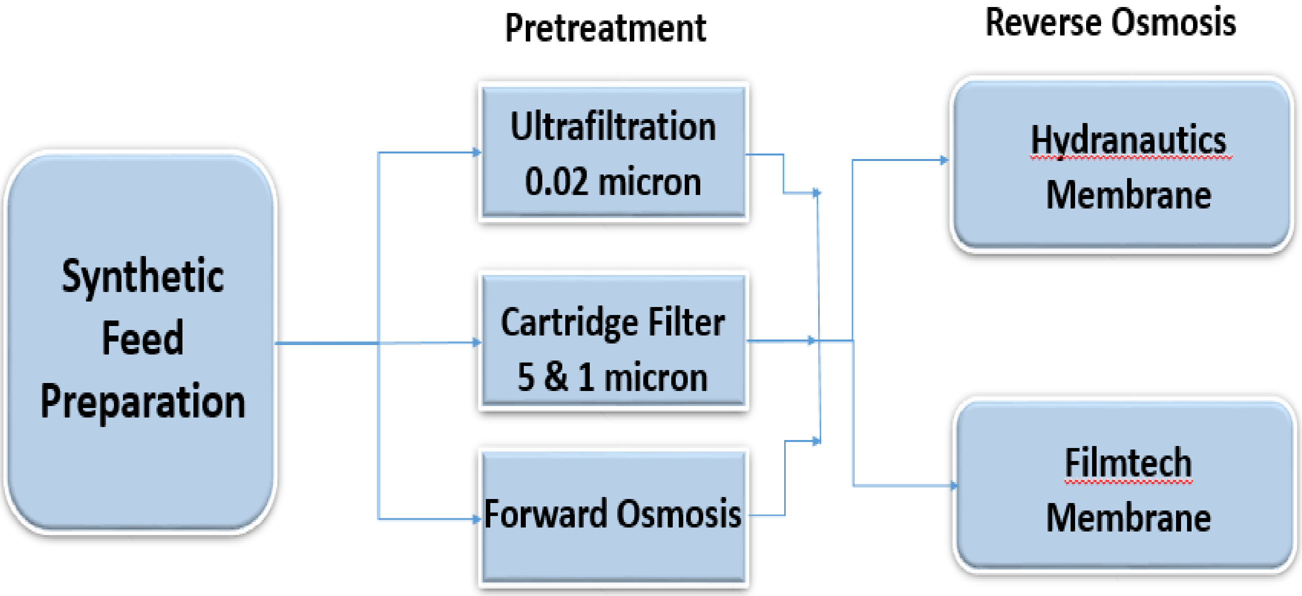

Figure 3.3: Process flow diagram

i. Ultra-filtration as a pre-treatment to RO (UF-RO)

In the first case, brackish water having concentration 3500, 4000, & 4500 mg/L were used as a feed for both RO membrane (i.e. Hydranautics CPA5-LD-4040 and Filmtech Lc-Le-4040). Brackish water was fed to both RO membranes after passing through 0.02 µm pore size ultra-filtration membrane. For each brackish water condition, system was ran for two hours for each set of recoveries 30, 35, 40, 45 & 50 percent achieved by throttling valve adjustment, the duration was sufficient enough to achieve the stabilize condition. Treated water known as permeate, achieved after passing through RO membrane went to clean in place (CIP) tank and the concentrated went to the feed tank. When CIP tank filled completely, level controller mounted in a tank turn off solenoid valve and divert the permeate flow toward feed tank to avoid new feed preparation and make operation continuous After each run, forward washing of RO membrane was done with treated water stored in a CIP tank with the help of CIP pump to avoid membrane surface deposition. Optimization and classification of the process performance was done on the basis of following parameters which includes, membrane inlet pressure, feed TDS, feed pH, membrane outlet pressure, permeate pH, and permeate TDS.

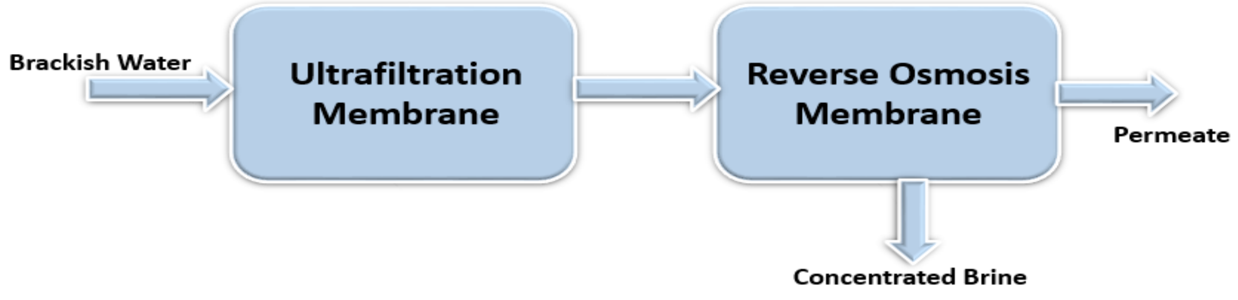

Figure 3.4: Block flow diagram of UF-RO combination

ii. 5 & 1 µm cartridge filter as a pre-treatment to RO (CF-RO)

In the second case, brackish water having concentration 3500, 4000, & 4500 mg/L were fed to both RO membranes (i.e. Hydranautics CPA5-LD-4040 and Filmtech Lc-Le-4040) after passing through 5 & 1 µm melt blown cartridge filter used as a pre-treatment.

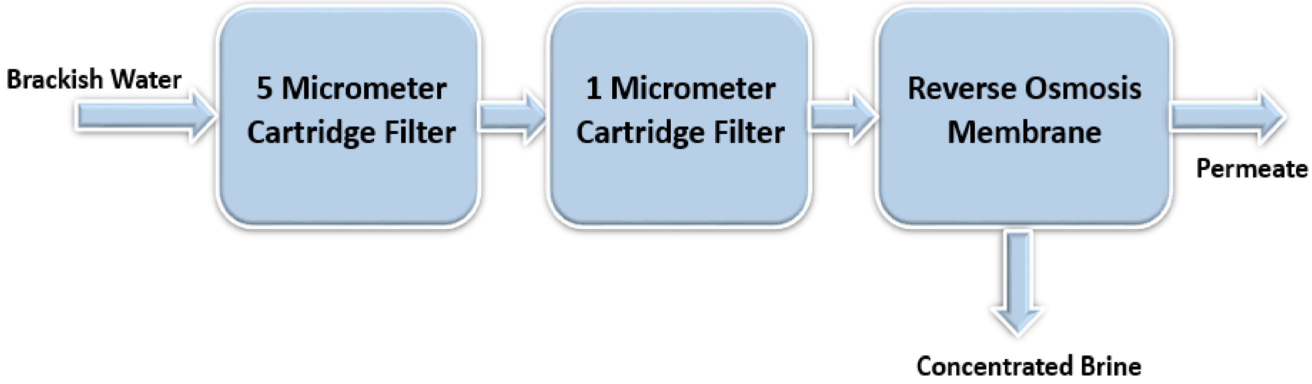

Figure 3.5: Block flow diagram of CF-RO combination

Figure 3.6: Cartridge filter after clogging

iii. Forward Osmosis as a pre-treatment to RO (FO-RO)

In the third case, forward osmosis (FO) membrane was used as a pre-treatment to both RO membrane. For forward osmosis as a pretreatment, 0.25 M feed solution (F.S) of NaCl and 0.25 of $MgCl_2$ was used as a draw solution (D.S). Actual picture of the FO membrane setup in shown in Fig. 15. Brackish water feed enters into a tank having submersible FO membrane module for the circulation of D.S. Water from feed side pass through FO membrane and moves toward D.S due to concentration gradient and dilute D.S. Flux across FO membrane was observed by digital data logger weight balance. The diluted D.S was then fed to the RO membrane for the separation of clean water and regeneration of D.S to reuse it as a draw solution.

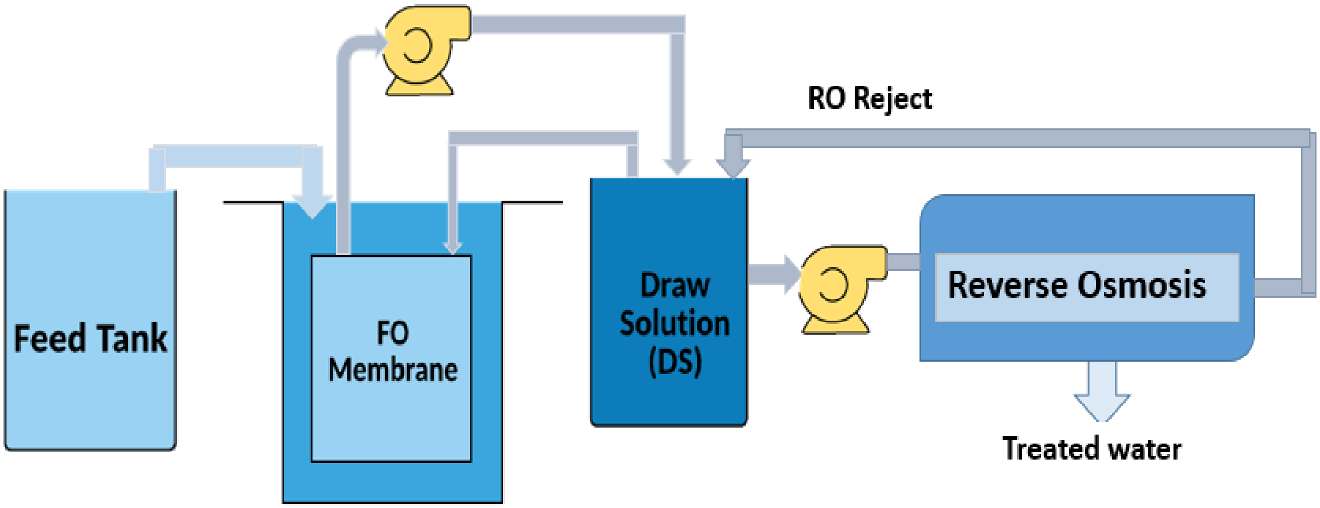

Figure 3.7: Block flow diagram of FO-RO combination

Figure 3.8: Bench Scale Forward Osmosis Setup

Results and discussion

4.1. Ultra-filtration (UF) as a pretreatment for reverse osmosis (RO)

It was found that 0.02 µm ultrafiltration membrane followed by RO membrane produced good quality portable water as compared to other pretreatment options coupled with a reverse osmosis membrane (i.e. CF-RO and FO-RO combination with NaCl as a draw solution).

4.1.1. Percent Rejection Vs. Recovery (Hydranautics)

The study revealed that the ultrafiltration membrane followed by Hydranautics membrane (CPA5-LD-4040) gave an average 98, 97 and 96 percent salt removal for brackish water feed having concentration 3500, 4000 and 4500 mg/L respectively for recoveries ranging from 35 to 50%

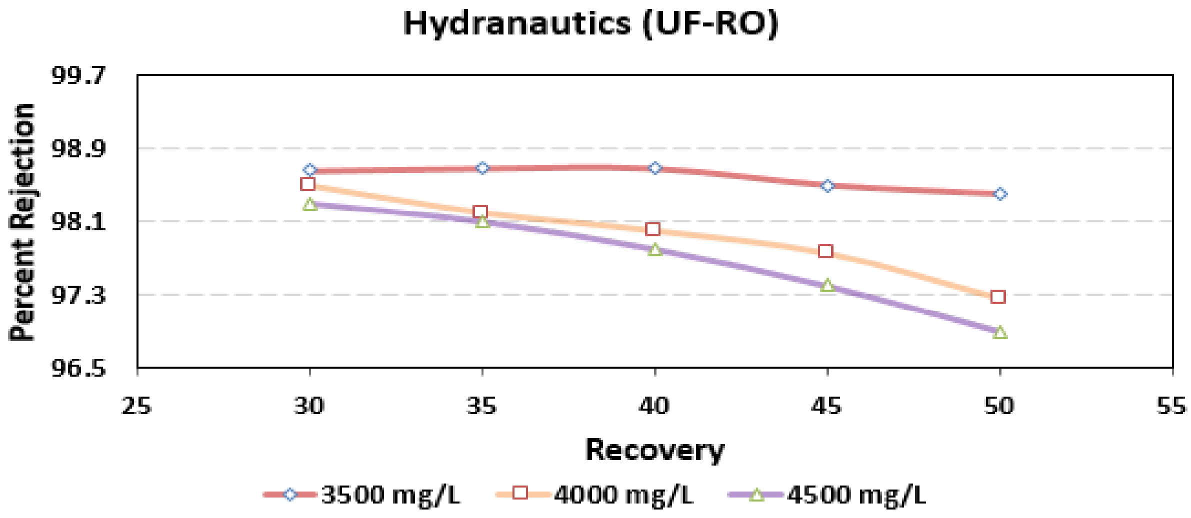

Figure 4.1. Percent rejection of Hydranautics membrane at different recoveries.

4.1.2. Percent Rejection Vs Pressure (Hydranautics)

It was also observed that, Hydranautics membrane preceded by 0.02 µm ultra-filtration membrane gave an average 1% decrease in rejection/bar increase in pressure for brackish water feed having concentration 4000 mg/L and 4500 mg/L while no significant decrease in rejection was observed for the brackish water having concentration of 3500 mg/L.

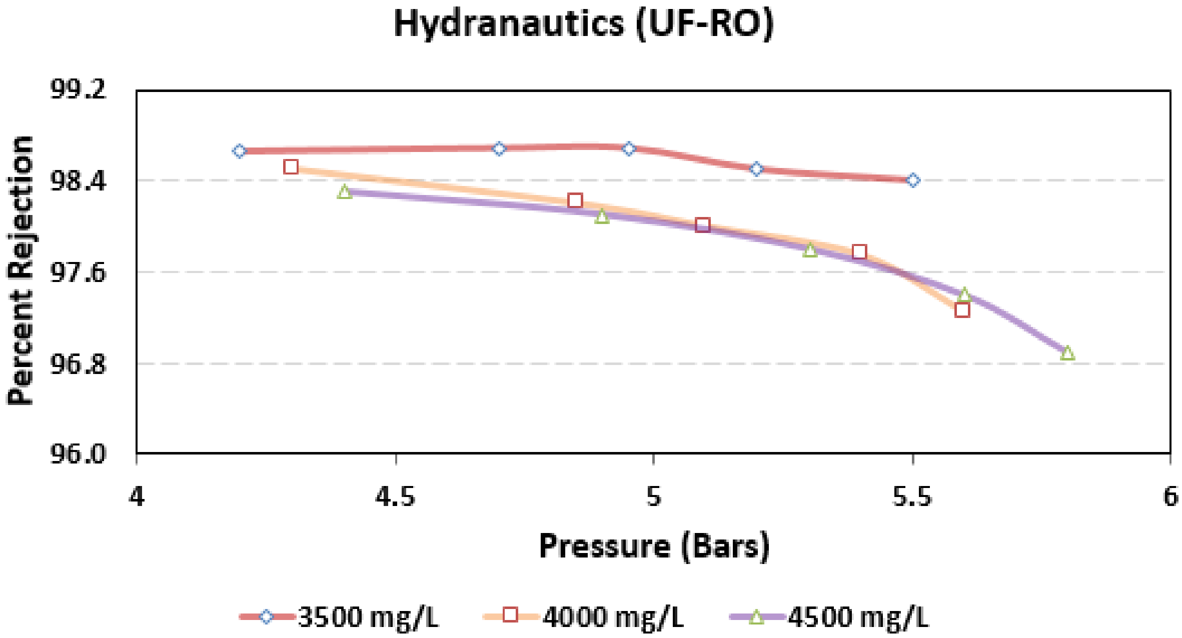

Figure 4.2. Percent rejection of Hydranautics membrane at different inlet pressure.

4.1.3. Percent Rejection Vs Recovery (Filmtech)

Filmtech membrane was also found very effective and gave excellent result in combination with 0.02 µm ultra-filtration membrane. It was found that, Filmtech membrane (Lc-Le-4040) preceded by 0.02 µm ultrafiltration membrane gave 99 percent removal for brackish water feed having concentration 3500 mg/L, while 98 percent rejection for observed for the brackish water feed having concentration 4000 and 4500 mg/L.

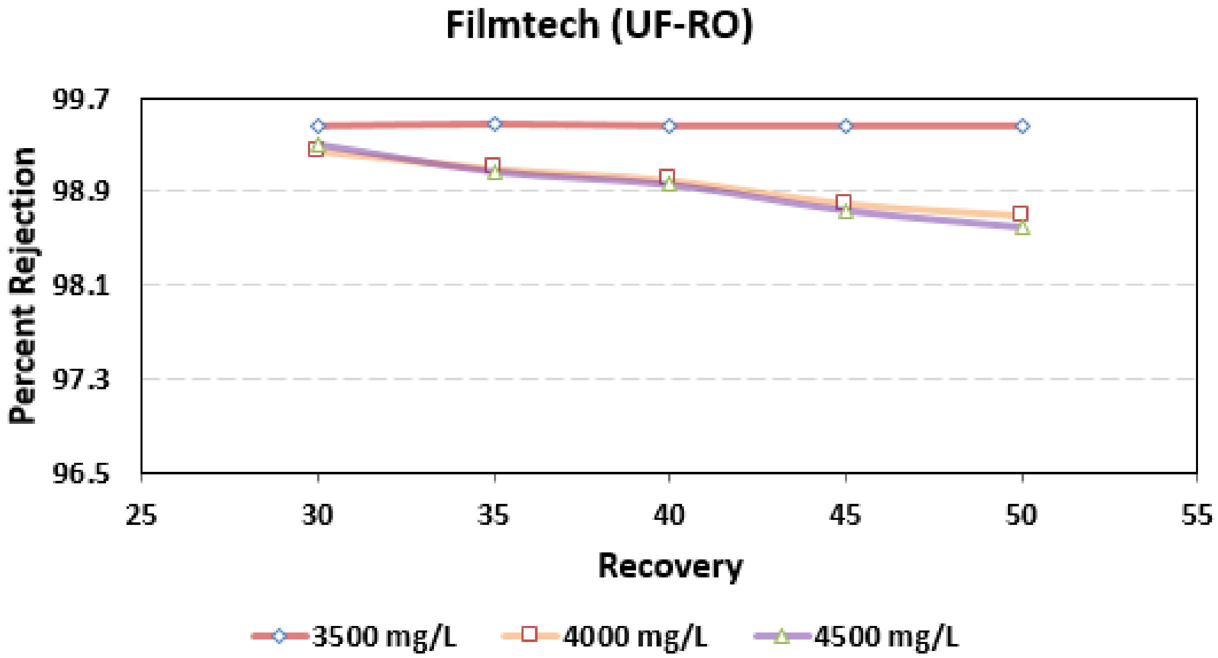

Figure 4.3. Percent rejection of Filmtech membrane at different recoveries.

4.1.4. Percent Rejection Vs Pressure (Filmtech)

It was also observed that, Filmtech membrane preceded by 0.02 μm ultra-filtration membrane gave an average 0.35 % decrease in rejection/ bar increase in pressure for brackish water feed having concentration 4000 and 4500 mg/L while no significant decrease in rejection was observed for the brackish water having concentration 3500 mg/L for water recoveries ranging from 30 to 50%

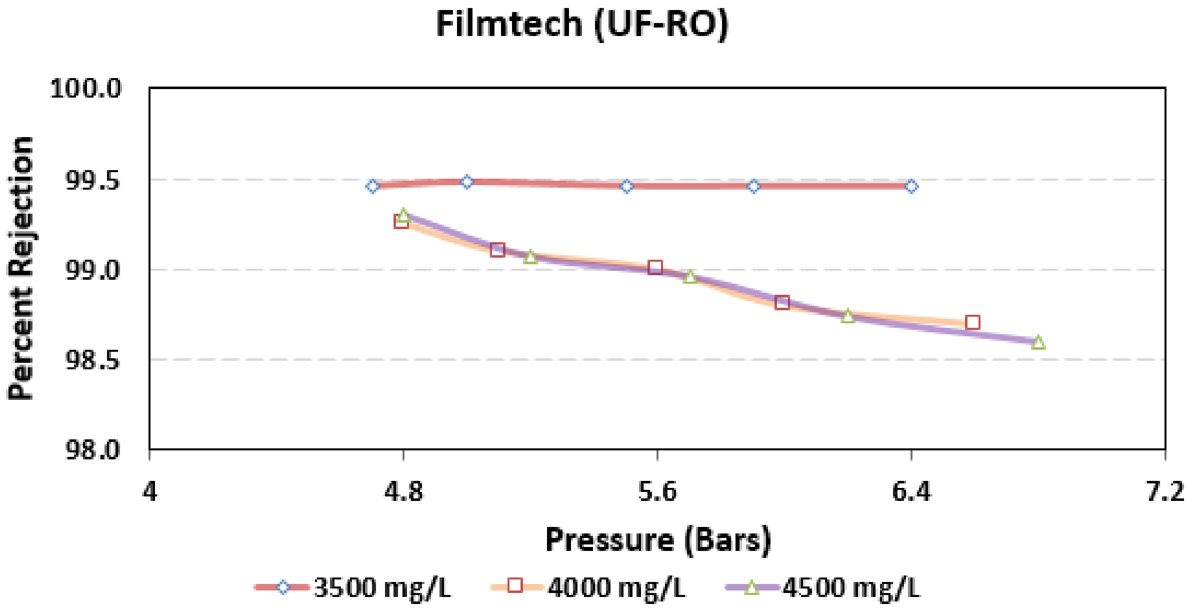

Figure 4.4. Percent rejection of Filmtech membrane at different inlet pressure.

4.2. Cartridge filter (5 & 1 µm) as a pretreatment for reverse osmosis (RO)

Melt blown cartridge filter was also found as an effective pretreatment option and shows high rejection with filmtech membrane. In this study 5 & 1 µm melt blown cartridge filter followed by reverse osmosis membrane gave good quality result as compared to FO-RO combination using NaCl as a draw solution but lower TDS rejection as compared to UF membrane

4.2.1. Percent Rejection Vs Recovery (Hydranautics)

It was found that the Hydranautics membrane preceded by 5 and 1 µm melt blown cartridge filter gave 86, 84 & 83 percent removal for brackish water feed having concentration 3500 mg/L, 4000 and 45 mg/L respectively. This rejection of TDS was not consistent over different recoveries as shown in figure 4.5.

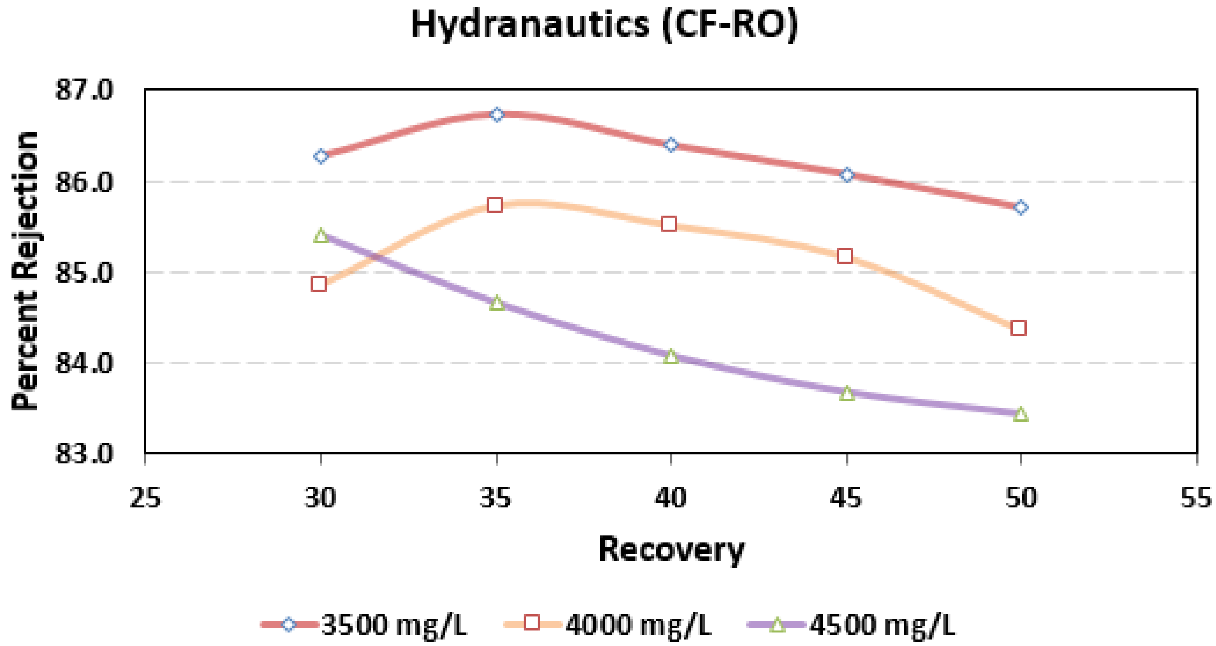

Figure 4.5. Percent rejection of Hydranautics membrane at different recoveries.

4.2.2. Percent Rejection Vs Pressure (Hydranautics)

It was also observed that, Hydranautics membrane preceded by 5 & 1 µm melt blown cartridge filter gave an average 1 % decrease in ejection/ bar increase in pressure for brackish water feed having concentration 3500, 4000 and 4500 mg/L

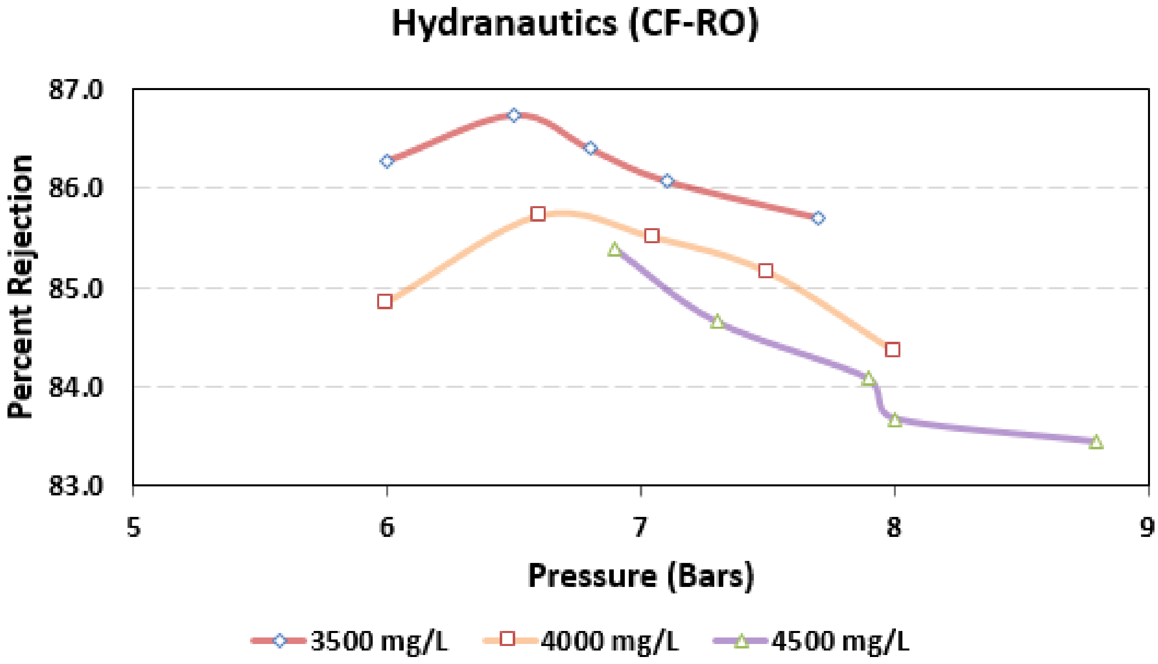

Figure 4.6. Percent rejection of Hydranautics membrane at different inlet pressure

4.2.3. Percent Rejection Vs Recovery (Filmtech)

In CF-RO combination Filmtech membrane was also found very effective and gave better quality results as compared with Hydranautic membrane. It was found that Filmtech membrane preceded by 5 and 1 µm melt blown cartridge filter gave 95, 95 & 94 percent removal for brackish water feed having concentration 3500, 4000 and 4500 mg/L respectively

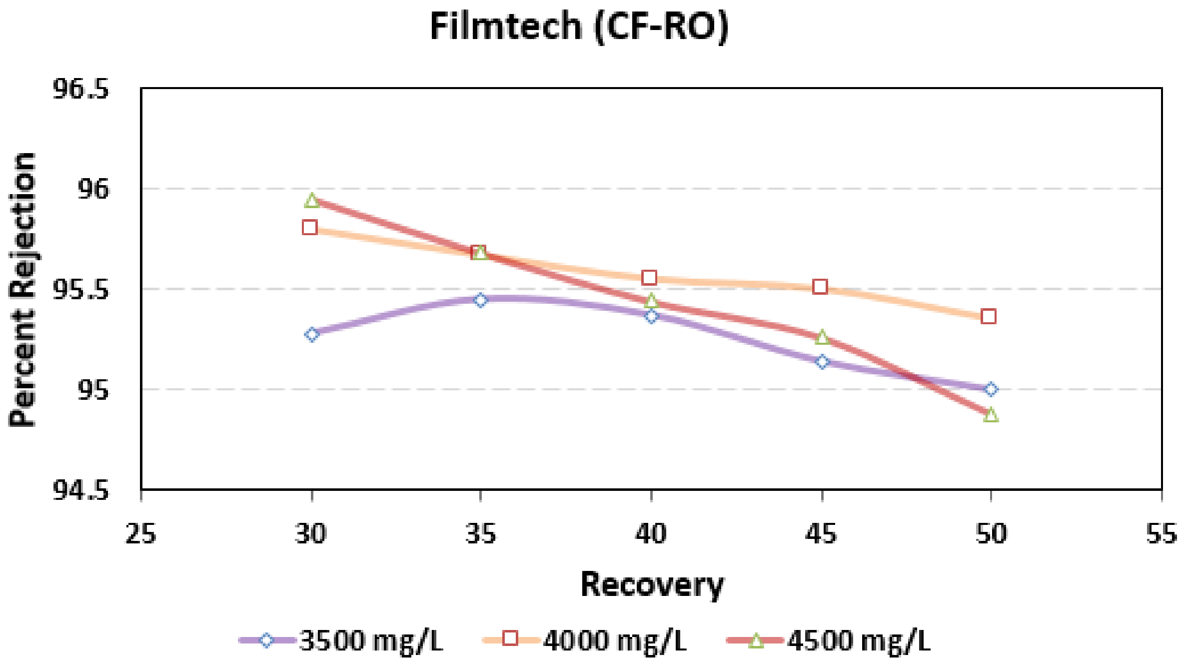

Figure 4.7. Percent rejection of Filmtech membrane at different recoveries.

4.2.4. Percent Rejection Vs Pressure (Filmtech)

Filmtech (LcLe-4040) gave an effective and sustainable operation over a wide range of pressure as compared with Hydranautics. It was also observed that, Filmtech membrane preceded by 5 & 1 µm melt blown cartridge filter gave average 0.6 % decrease in rejection/ bar increase in pressure for brackish water feed having concentration 3500, 4000 and 4500 mg/L

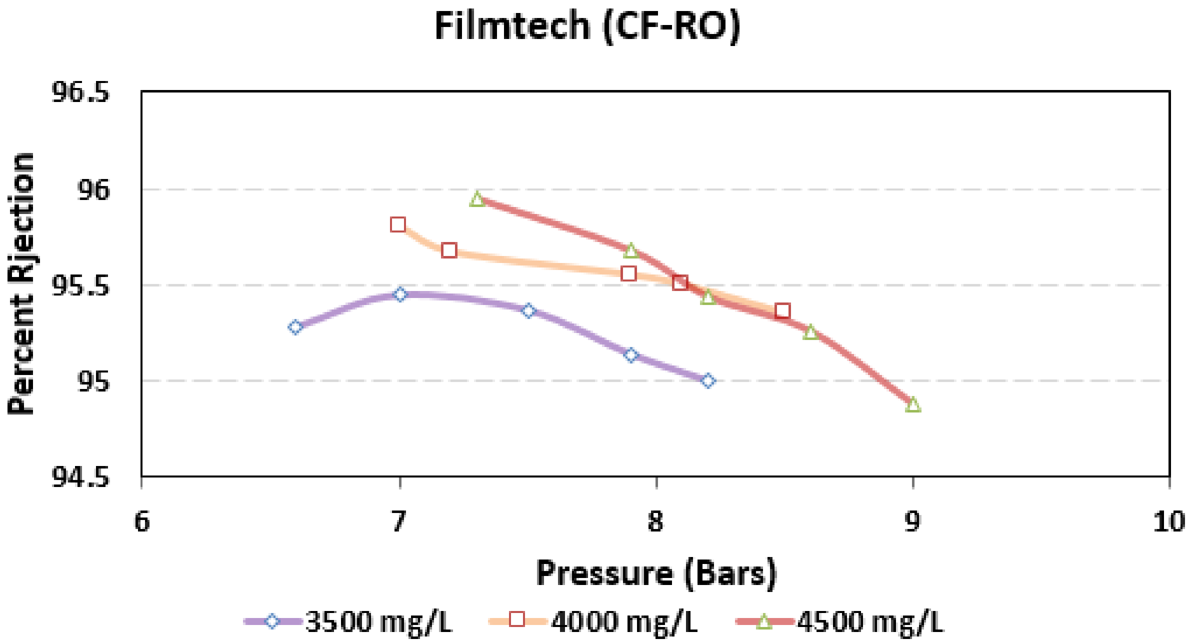

Figure 4.8. Percent rejection of Filmtech membrane at different inlet pressure

4.3. Forward Osmosis (FO) as a pretreatment for reverse osmosis (RO)

Forward osmosis (FO) was also found an effective pretreatment option for RO membrane, it was observed that the flux across the FO membrane has a direct relation to the molar concentration of draw solution and inverse with the feed concentration.

4.3.1. Percent Rejection Vs Recovery (Hydranautics)

It was found that the FO-RO combination with the Hydranautic membrane using NaCl as a draw soltion gave 78, 76 and 73 percent removal for brackish water feed having concentration 3500, 4000 and 4500 mg/L respectively

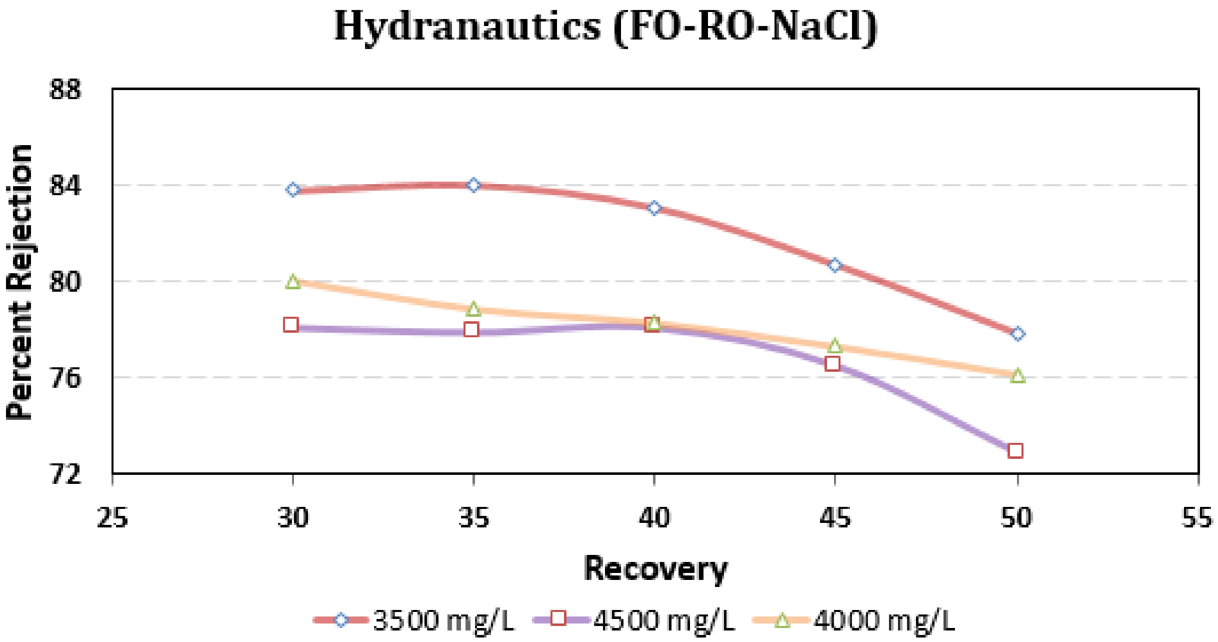

Figure 4.9. Percent rejection of Hydranautics membrane at different recoveries.

4.3.2. Percent Rejection Vs Pressure (Hydranautics)

It was also observed that the Hydranautics (CPA5-LD-4040) membrane preceded by cellulose triacetate (CTA) forward osmosis (FO) membrane with NaCl as a draw soltion gave an average 3.7 percent decrease in rejection/bar increase in pressure for brackish water feed having concentration 3500, 4000 and 4500 mg/L with less fouling potential to RO membrane as compared to UF-RO & CF-RO combination due to presence of pure NaCl used as a draw solution.

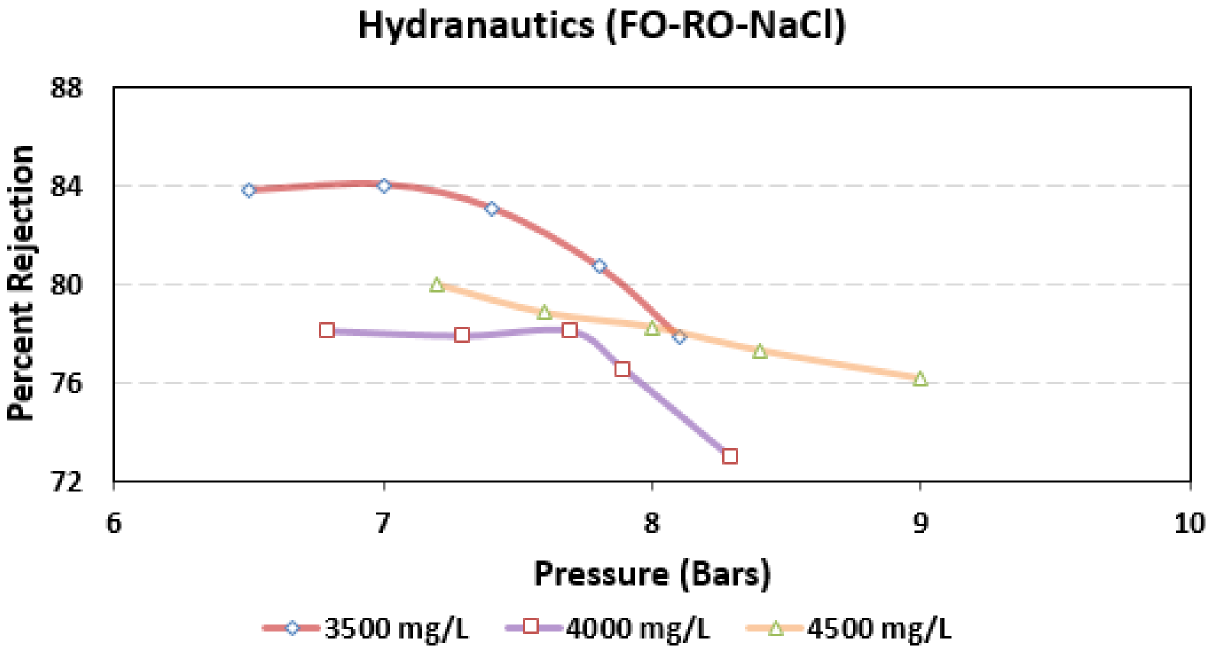

Figure 4.10. Percent rejection of Hydranautics membrane at different inlet pressure

4.3.3. Percent Rejection Vs Recovery (Filmtech)

Filmtech membrane preceded by forward osmosis membrane also found very effective and gave high quality result as compared with Hydranautics membrane. It was found that the FO-RO combination with the Filmtech membrane using NaCl as a draw soltion gave 96, 95 and 95 percent removal for brackish water feed having concentration 3500, 4000 and 4500 mg/L respectively

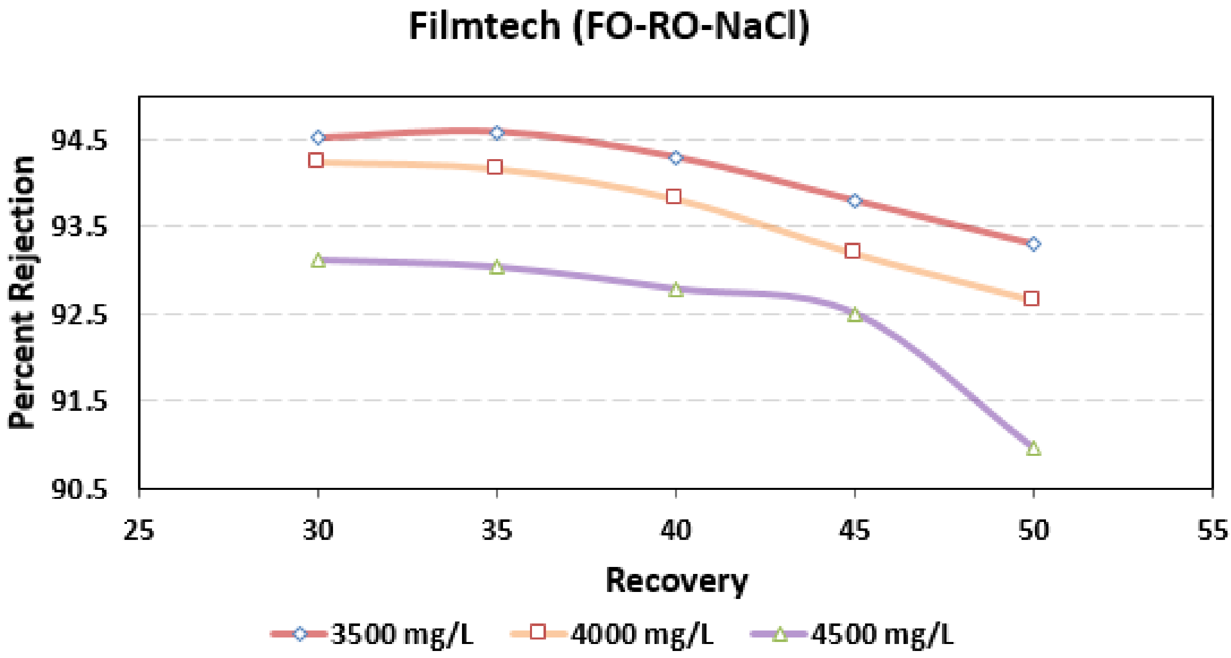

Figure 4.11. Percent rejection of Filmtech membrane at different recoveries

4.3.4. Percent Rejection Vs Pressure (Filmtech)

It was also observed that the Filmtech (LcLe-4040) membrane preceded by cellulose triacetate (CTA) forward osmosis (FO) membrane with NaCl as a draw solution gave an average 1 percent decrease in rejection/bar increase in pressure for brackish water feed having concentration 3500, 4000 and 4500 mg/L with less fouling potential to RO membrane as compared to UF-RO & CF-RO combination due to presence of pure NaCl used as a draw solution.

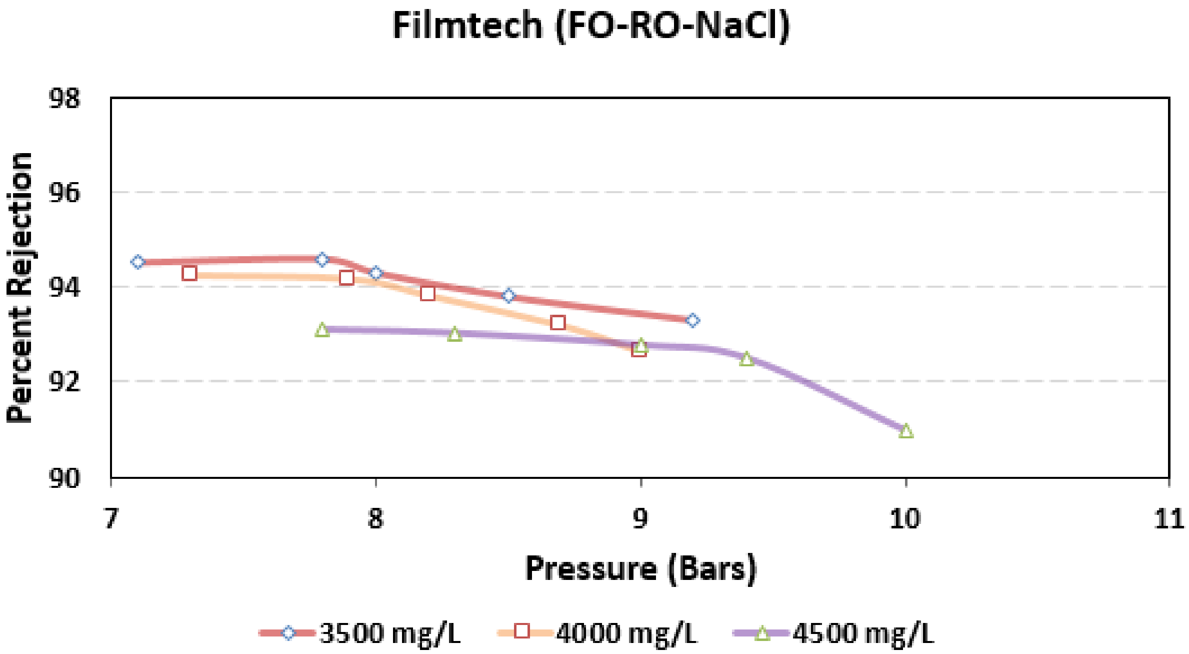

Figure 4.12. Percent rejection of Filmtech membrane at different inlet pressure

4.3.5. Percent Rejection Vs Recovery (Hydranautics)

It FO-RO combination with the Hydranautics membrane using $MgCl_2$ as a draw soltion gave good quality results as compared to other pretreatment option including utrafiltration, 5 & 1 µm cartridge filter and forward osmosis with NaCl as a draw solution and gave 96, 95 & 95 percent salt rejection for brackish water feed having concentration 3500, 4000 and 4500 mg/L respectively.

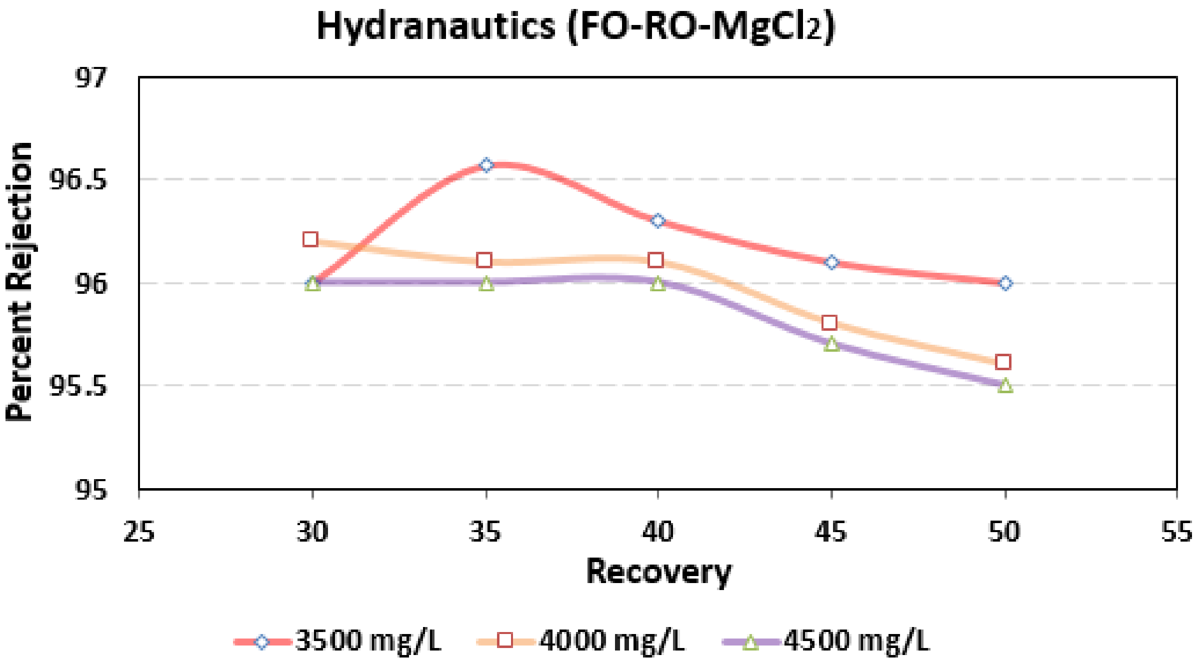

Figure 4.13. Percent rejection of Hydranautics membrane at different recoveries

4.3.6. Percent Rejection Vs Pressure (Hydranautics)

It was also observed that the Hydranautics (CPA5-LD-4040) membrane preceded by cellulose triacetate (CTA) forward osmosis (FO) membrane with $MgCl_2$ as a draw soltion gave an average 0.27 percent decrease in rejection/bar increase in pressure for brackish water feed having concentration 3500, 4000 and 4500 mg/L with less fouling potential to RO membrane as compared to UF-RO & CF-RO combination due to presence of pure $MgCl_2$ used as a draw solution.

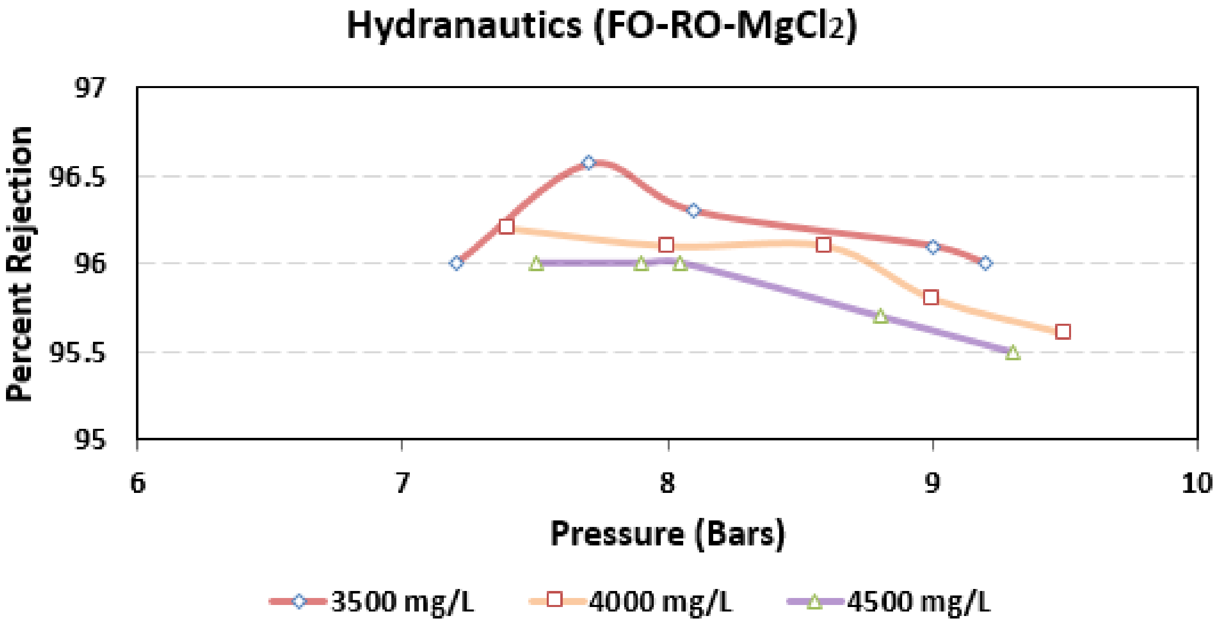

Figure 4.14. Percent rejection of Hydranautics membrane at different inlet pressure

4.3.7. Percent Rejection Vs Recovery (Filmtech)

FO-RO combination with Filmtech membrane using $MgCl_2$ as a draw soltion gave good quality results as compared to other pretreatment option including utrafiltration, 5 & 1 µm cartridge filter and forward osmosis with NaCl as a draw solution and gave overall 97 percent salt rejection for brackish water feed having concentration 3500, 4000 and 4500 mg/L.

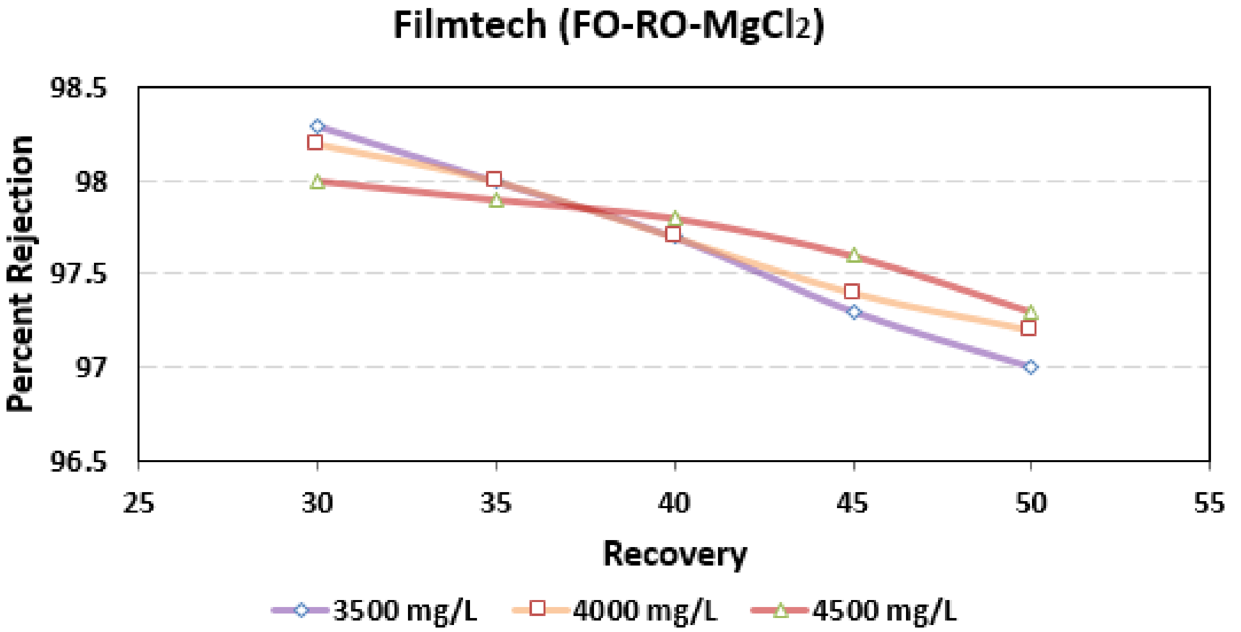

Figure 4.15. Percent rejection of Filmtech membrane at different recoveries

4.3.8. Percent Rejection Vs Pressure (Filmtech)

It was also observed that the Filmtech (LcLe-4040) membrane preceded by cellulose triacetate (CTA) forward osmosis (FO) membrane with $MgCl_2$ as a draw soltion gave an average 0.61 percent decrease in rejection/bar increase in pressure for brackish water feed having concentration 3500, 4000 and 4500 mg/L with less fouling potential to RO membrane as compared to UF-RO & CF-RO combination due to presence of pure $MgCl_2$ used as a draw solution.

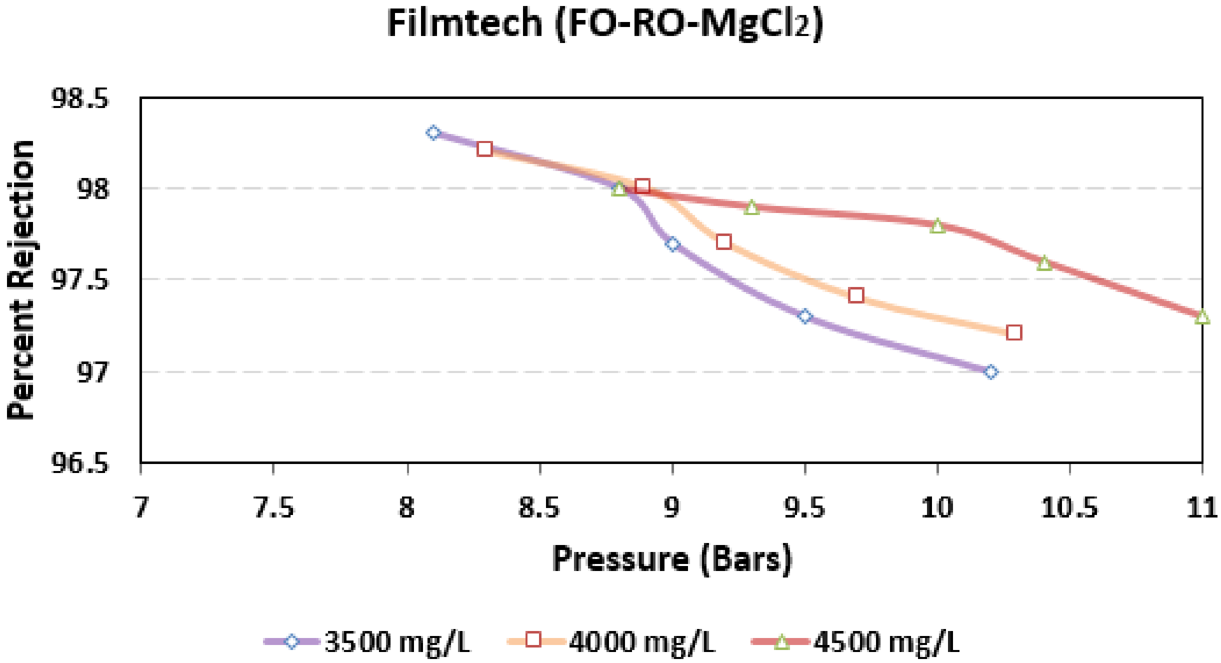

Figure 4.16. Percent rejection of Fillmtech membrane at different inlet pressure

Chapter 5

Conclusions and Recommendation

5.1. Conclusions

Filmtech membrane Lc-Le-4040 gave better performance than the Hydranautics membrane CPA5-LD-4040 with all three pretreatment technologies. Both RO membranes were thin film composite (TFC). However the main reason behind this varying performance is the use of different types of binding agents and membrane wrapping mechanism. Brackish water feed with high TDS value required higher operating pressure for the separation of water from salt resulting in greater up-thrust between membrane layers and eventually decline in membrane performance.

Forward Osmosis was found as an effective pretreatment option and gave 90 and 97 percent removal for NaCl and $MgCl_2$ used as a draw solution in combination with Filmtech membrane while Hydranautics membrane gave 73 and 95 percent removal efficiency for NaCl and $MgCl_2$ with less fouling potential but at high operating cost as compared to other treatment options due to its high TDS value (RO feed). In FO-RO combination, use of $MgCl_2$ as draw solution gave better results as compared with NaCl due to its divalent structure (Mg^{+2}). UF-RO combination with both Filmtech & Hydranautics were also very effective and gave 96-98 percent removal efficiency but has more fouling potential as compared to FO-RO combination. CF-RO combination was also very effective as compared to FO-RO with NaCl as a draw solution and gave 83 and 94 percent removal with Hydranautics and Filmtech but also has high fouling potential.

5.2. Recommendations

1. Different types of membrane can be used for the similar set of arrangement to check their performance.
2. Ultra-filtration membrane or Nano-filtration membrane can be incorporate with Forward Osmosis setup for the treatment of concentrated brackish water discharge from FO module after fresh water extraction to achieve high recovery.
3. Similar membrane or other different RO membrane can be used to check Heavy metal rejection.

Reference:

Achilli, A., Cath, T.Y., Marchand, E.A. and Childress. A.E. 2009 The forward osmosis membrane bioreactor: a low fouling alternative to MBR process, Desalination, 239, 10-21

Al-Mutaz I, Al-Namlah A. Characteristic of dual purpose MSF desalination plants. Desalination 2004; 166:59-79

Arras, W., Ghaffour, N., & Hamou, a. (2009). Performance evaluation of BWRO desalination plant—A case study. *Desalination*, *235*(1-3), 170–178.

Baker, R. W. (2004). Membrane Technology and Applications, 2nd ed.; John Wiley & Sons, Ltd.

Buros OK. The ABC of desalination. 2nd ed. Riyadh, S.A: Produced by The Saline Water Conversion Council for the International Desalination Association: 2000 2000.

Carlos Garcia, Francisco Molina, Domingo Zarzo, 7 year operation of a BWRO plant with raw water from a coastal aquifer for agricultural irrigation, Desalin. Water Treat. 31 (2011) 331–338.

D.L. Shaffer, N.Y. Yip, J. Gilron, M. Elimelech, Seawater desalination for agriculture by integrated forward and reverse osmosis: improved product water quality for potentially less energy, J. Membr. Sci. 415–416 (2012) 1–8.

Darwish MA. Thermal analysis of MSF desalting systems. Journal of desalination 1991;85:59-79.

G. Pearce, SWRO pre-treatment: markets and experience, Filtr. Sep. 47 (2010) 30–33

Ghaffour, N., Missimer, T. M., & Amy, G. L. (2013). Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. *Desalination*, *309*(2013), 197–207.

Global Water Intelligence (GWI/WDR), Market profile and desalination markets, 2011. Yearbooks and GWI website: http://www.desaldata.com/.

H. Mahmoudi, A. Ouagued, N. Ghaffour, Capacity building strategies and policy for desalination using renewable energies in Algeria, Renew. Sustain. Energy Rev. 13 (2009) 921–926.T.

Hancock, N.T., Black, N.D. and Cath, T.Y. 2012 A comparative life cycle assessment of hybrid osmotic dilution desalination and established seawater desalination and wastewater reclaimation processes, Water Res. 46, 1145-1154.

Jamaly, S., Darwish, N. N., Ahmed, I., & Hasan, S. W. (2014). A short review on reverse osmosis pretreatment technologies. *Des*, *354*, 30–38.

Jin, X., She, Q., Ang, X. and Tang, C.Y. 2012a Removal of boron and arsenic by forward osmosis membrane: Influence of membrane orientation and organic fouling. J. Membrane Sci. 389, 182-187.

Kwon, B., Park, N. and Cho, J. (2005). Effect of algae on fouling and efficiency of UF membrane Desalination 179: 203–214.

L.F. Greenlee, D.F. Lawler, B.D. Freeman, B. Marrot, P. Moulin, Reverse osmosis desalination: water sources, technology, and today's challenges, Water Res. 43 (2009) 2317–2348.

Miller, JE. Review of water resources and desalination technologies, Sandia Laboratories, SAND 2003-0800

Morillo, J., Usero, J., Rosado, D., El Bakouri, H., Riaza, A., & Bernaola, F. J. (2014). Comparative study of brine management technologies for desalination plants. *Desalination*, *336*, 32–49.

Muhammad, N., & Alam, M. M. (n.d.). Prospectives and Limits of Groundwater Use in Pakistan, (i). [Perspective of PK]

N. Ghaffour, The challenge of capacity-building strategies and perspectives for desalination for sustainable water use in MENA, Desalin. Water Treat. 5 (2009) 48–53.

N. Misdan, W.J. Lau, A.F. Ismail, Seawater Reverse Osmosis (SWRO) desalination by thin film composite membrane—current development, challenges and future prospects, Desalination 287 (2012) 228–237.

Reig P., Maddocks, A. and Gassert, F. (2013). Aqueduct Country and River Basin Rankings. World Resources Institute.

S.G.J. Heijman, H. Guo, S. Li, J.C. van Dijk, L.P. Wessels, Zero liquid discharge: heading for 99% recovery in nanofiltration and reverse osmosis, Desalination 236 (2009) 357–362

Sagle, A. and Freeman, B. (2004). Fundamentals of membranes for water treatment. The Future of Desalination in Texas, vol. II, Texas Water Development Board, Austin, TX: 137–153.

Tianyu Qiu, Philip A. Davies, Comparison of configurations for high-recovery inland desalination systems, Water 4 (2012) 690–706.

UNDP: Human Development Report (2006). Beyond scarcity: Power, poverty and the global water crisis.

UNEP, 21 Issues for the 21st Century: Result of the UNEP Foresight Process on Emerging Environmental Issues, Kenya, Nairobi, 2012. 56.

V.B.A. Brehant, M. Perez, Comparison of MF/UF pretreatment with conventional filtration prior to RO membranes for surface seawater desalination, Desalination 144 (2002) 353–360.

Yen, S.K., Mehnas, F., Haja, N., Su, M., Wang, K.Y. and Chang, T.S. 2010 Study of draw solutes using 2-methylimidazole-based compounds in forward osmosis, J. Member. Sci, 364, 242-252.

Younos T. and Tulou, K. E. (2009). Overview of Desalination Techniques. Journal of contemporary Water Research and Education 132: 3-10

Youssefa, P.G., Al-Dadaha*, R.K. and Mahmouda, S.M. (2014). Comparative Analysis of Desalination Technologies. Energy Procedia 61: 2604-2607