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Seawater Desalination Characteristics Using Variable Combinations of NF and RO Membranes

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إقـــرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

Seawater Desalination Characteristics Using Variable Combinations of NF and RO Membranes

خصائص تحلية مياه البحر باستخدام تراكيب مختلفة من فلاتر النانو فلتر وفلاتر التناضح العكسي

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واللجنة إذ تمنحه هذه الدرجة فإنها توصيه بتقوى الله ولزوم طاعته وأن يسخر علمه في خدمة دينه ووطنه.

والله ولي التوفيق ،،،

نائب الرئيس لشئون البحث العلمي والدراسات العليا

أ.د. عبدالرؤوف علي المناعمة

ABSTRACT

Gaza Strip is considered one of the poorest and most limited water resources area in the region. RO desalination technology is strongly recommended and considered as a strategic alternative to meet the future needs of water for the Strip. The shortage of energy source becomes a big constrain facing desalination plants. Nanofiltration technology with less operation pressure, high flux and high rejection rate of salt ions can save energy and cost of desalination.

The main goal of this research is to investigate seawater desalination characteristics using variable combination of NF and RO membrane to save energy consumption. Three types of spiral wound modules of (2.5") including nanofiltration membrane (NF90-2540), RO seawater membrane (SW30-2540) and RO brackish water membrane (BW-2540) were variably installed in a pilot desalination unit. A series of experiments were carried out varying the applied pressure and flow rate from both feed seawater and brine recirculation to identify the best combination of NF and RO membranes in desalination process in terms of Specific Energy Consumption (SEC) of one cubic meter of permeate. A combination of *six* RO seawater membranes in series as a first pass of desalination at 60 bar pressure followed by *one* NF membrane as a second pass of desalination at 10 bar pressure achieved the lowest SEC value (7.94 kW/m^3) and the obtained Cl concentration in permeate is (9 mg/l). The second lowest SEC value (9.23 kW/m^3) was obtained when *six* NF membranes in series was used as a first pass of desalination at 37 bar pressure followed by *one* NF membrane as a second pass of desalination at 30 bar pressure. The obtained Cl concentration in permeate is (225 mg/l). In other hand, the recovery rate obtained from using one NF membrane with 87% brine recirculation ratio, is equivalent to that of using fife elements in series in one vessel without brine recirculation.

Accordingly, NF membranes as well as brine recirculation should be used in desalination process in Gaza Strip.

الملخص

يعتبر قطاع غزة من المناطق الأكثر فقرا ومحدودية في مصادر المياه. وتعتبر عملية تحلية مياه البحر باستخدام تقنية التناضح العكسي هي الخيار الاستراتيجي الأمثل لتلبية الاحتياجات المتزايدة للمياه في قطاع غزة الا ان مشكلة العجز في مصادر الطاقة اللازمة لتحلية المياه يعتبر العقبة الأكبر وذلك نظرا لما تتطلبه هذه التقنية من طاقة كبيرة. وحيث ان اغشية النانو تمتاز باحتياجها الى كمية اقل من الطاقة وكذلك بالقدرة العالية على إزالة الاملاح تحت ضغوط اقل من تلك اللازمة لأغشية التناضح العكسي. يهدف هذا البحث الى دراسة خصائص عملية تحلية مياه البحر باستخدام تراكيب مختلفة من اغشية النانو واغشية التناضح العكسي لتوفير استهلاك الطاقة. ومن اجل ذلك تم بناء وحده تحلية صغيرة باستخدام ثلاثة أنواع من اغشية التحلية وهي غشاء النانو (NF90-2540) وغشاء التناضح العكسي لمياه البحر (SW30-2540) وغشاء التناضح العكسي للمياه المالحة (BW-2540). حيث أجريت العديد من التجارب تحت ضغوط مختلفة وكذلك تم اختبار تأثير إعادة تدوير المياه العادمة (Brine) بنسب مختلفة من اجل الوصول الى التركيب الذي يحقق الاستهلاك الأقل للطاقة. حيث تبين ان استخدام ستة عناصر من أغشية التناضح العكسي الخاصة بمياه البحر موصولة على التوالي تحت ضغط ٦٠ بار في المرحلة الأولى من التحلية متبوعا باستخدام غشاء نانو واحد تحت ضغط ١٠ بار في المرحلة الثانية من التحلية يحقق الاستهلاك الأقل للطاقة (٧,٩٤ ك وات / م^{٣}) وتركيز الكلوريد في المياه المحلاة هو (٩ ملغ/ لتر). ويليه استخدام ستة عناصر من اغشية النانو موصولة على التوالي تحت ضغط ٣٧ بار في المرحلة الأولى من التحلية متبوعا باستخدام غشاء نانو واحد تحت ضغط ٣٠ بار في المرحلة الثانية من التحلية، حيث ان قيمة الطاقة المستهلكة تساوي (٩,٢٣ ك وات / م^{٣}) و تركيز الكلوريد في المياه المحلاة هو(٢٢٥ ملغ/لتر) . كما تبين من التجارب ان استخدام عنصر واحد من اغشية النانو مع نسبة تدوير ٨٧% للمياه العادمة ينتج عنه معدل استنقاذ يعادل ذلك الناتج عن استخدام خمسة عناصر من اغشية النانو بدون إعادة تدوير. وبهذا فان الدراسة توصي باستخدام اغشية النانو مع إعادة تدوير المياه العادمة الناتجة عن التحلية في تحلية مياه البحر في قطاع غزة.

DEDICATION

This research is dedicated to:

My Father and Mother for their love pray, and continuous sacrifices…

To my wife for day and night unlimited support

To My Father and mother in law, how spared no effort to accomplish this work

TO my sons Husain, Nael, Abd El Rahman and my daughter Tala

To all of my brothers and sisters

To all of my friends and colleagues …

Redwan Husain Abu Krayeem

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LIST OF ABBREVIATIONS

Co	Salt Concentrations in the Feed Solution
Cp	Salt Concentrations In the Permeate
ED	Electrodialysis
EFC	Eutectic Freezing Crystallization
ETA	Abdul Salam Yaseen Company for water desalination plants and purification Systems.
Jv	Flux rate ($L.h^{-1}.m^{-2}$)
Lp	Hydraulic Permeability ($L.h^{-1}.m^{-2}.bar^{-1}$)
MEE	Multiple-effect evaporation
MF	Microfiltration
MSF	Multi-Stage Flash
NF	Nanofiltration
PAN	Polyacrylonitrile
Pc	Concentrate pressure
Pc	Critical pressure
PEEK	Polyether Ether Ketone
PES	Polyethersulfone
Pf	Feed Pressure
Pp	Permeate pressure
ppm	Part per Million
PS	Polysulfone
PVDF	Polyvinyledene Fluoride
PWA	Palestinian Water Authority
Q_f	Feed flow rate (L/hr)
Q_p	Permeate flow Rate (L/hr)
Q_p	Permeate flow rate (L/hr)
R	Rejection rate (%)
RO	Reverse Osmosis
TDS	Total Dissolved Solids
TFC	Thin Film Composite
TOC	Total Organic Carbon
UF	Ultrafiltration
VC	Vapor Compression

WHO	World Health Organization
Y	Recovery Rate (%)
η	Global pumping system efficiency
ΔP	Trans-membrane pressure

LIST OF UNITS

MCM	Million Cubic Meter
Km	Kilometer
Km^2	Square Kilometer
m^2	Square meter
m^3	Cubic meter
mg/l	Milligrams per Liter
mm	Millimeter
nm	Nanometer
V	Volume
µm	Micrometer
V	Volume

CHAPTER ONE: INTRODUCTION

1.1 Background

According to the World Health Organization, total dissolved solids (TDS) should be less than 1000 mg/L in drinking water based on taste considerations (WHO, 2006). By comparison, seawater has an average TDS of about 35000 mg/L. Thus the vast majority of the earth's readily available water is too saline for potable use, and yet much of the world's fresh water is trapped in polar icecaps (2.5%) or is located far underground (Bindra et al. 2001). It is estimated that 0.014% of the world's water is easily accessible and has acceptable salinity levels. (Medeazza et al. 2004). The Gaza Strip is facing a challenge of water shortage and the unbalanced municipal water supply-demand situation. The extraction from coastal aquifer is almost twice the available recharge that has resulted in fresh water level decline by 20-30 cm per year (PWA, 2000). The groundwater quality in Gaza Strip varies from place to another and from depth to another, the chloride ion concentration varies from less than 250mg/L in the sand dune areas as the northern and south-western area of the Gaza Strip to about more than 10,000mg/L where the seawater intrusion has occurred. Also, The nitrate ion concentration reaches a very high range in different areas of the Gaza Strip, while the WHO standard recommended nitrate concentration less than 50mg/L (CMWU, 2011).

The history of membrane demineralization using reverse osmosis (RO) dates from the 1960s. Hence, the high pressures traditionally used in RO resulted in a considerable energy cost was first dedicated to seawater. Thus, RO membranes with lower rejections of dissolved components, but with higher water permeability, appeared to be of great improvement for separation technology, and low pressure RO membranes appeared dedicated to partial demineralization of brackish waters. (Conlon, 1985). The interest in low pressure RO had become established, specially for water softening and the first applications of NF was born, as detailed in a recent review (Hilal et al. 2004). NF offers several advantages in comparison to RO such as low operation pressure, high flux, high retention of multivalent anion salts and organics compounds relatively low investment and low operation/maintenance costs. Because of these advantages, the applications of Nanofiltration (NF) worldwide have increased. Today 10% of brackish waters market in the world is destined to (NF) membranes (Rovel, 2004). Research is continuing in an attempt to understand and model the varying parameters involved in NF.

1.2 Problem Statement

The coastal aquifer, which is considered as the main water resource in the Gaza Strip, is intensively exploited through more than four thousands of pumping wells, as a result of this intensive exploitation, the aquifer has been experiencing seawater intrusion in many locations in the Gaza Strip (Aish, 2010). Desalination became a strategic option in Palestine, its cost competes with the costs of other non-conventional water resources such as wastewater reuse and groundwater recharge (Sheikh et al., 2003). It can participate in a significant role in the sustainability of the water resources, the cost of desalination is still relatively expensive for our case in the Gaza Strip. Reverse osmosis desalination is strongly recommended and considered as a strategic alternative in order to overcome the water deficit and meet the future needs of water for the Strip, the shortage of energy source become a big constrain facing desalination plants of which these plants are operating at limited operational hours (Mogheir and Albahnasawi, 2014). Nanofiltration technology with less operation pressure, high flux, high rejection rate of multivalent anion salt can save energy and cost of desalination.

Because of that, the need of test variable combination of Nanofiltration and Reverse Osmosis membrane to save energy is required.

1.3 Goal

The main goal of this research is to save energy consumption in seawater desalination by using variable combinations of NF and RO membranes.

1.4 Specific Objectives

To be more specific, the Specific objectives of this search are:

- Investigate the seawater desalination characteristics when using NF membrane under variable feed operating pressure.
- Investigate the impact of brine recirculation on recovery rate, flux rate and ions removal.
- Investigate the seawater desalination characteristics when using RO element under variable feed operating pressure.
- Investigate the seawater desalination characteristics when using NF membrane in two passes of desalination.
- Investigate the seawater desalination characteristics when using NF membrane as a first pass of desalination and RO brackish water membrane as a second pass of desalination.
- Investigate the seawater desalination characteristics when using RO seawater water membrane as a first pass of desalination and NF membrane as a second pass of desalination.

- Investigate the seawater desalination characteristics when using RO seawater water membrane as a first pass of desalination and RO brackish water membrane as a second pass of desalination.
- Calculate Specific Energy Consumption (ESC) in each case.
- Optimizing the most economical choice of seawater desalination.

1.5 Methodology

It is intended to achieve the study objectives by the following steps shown in Figure (1-1):

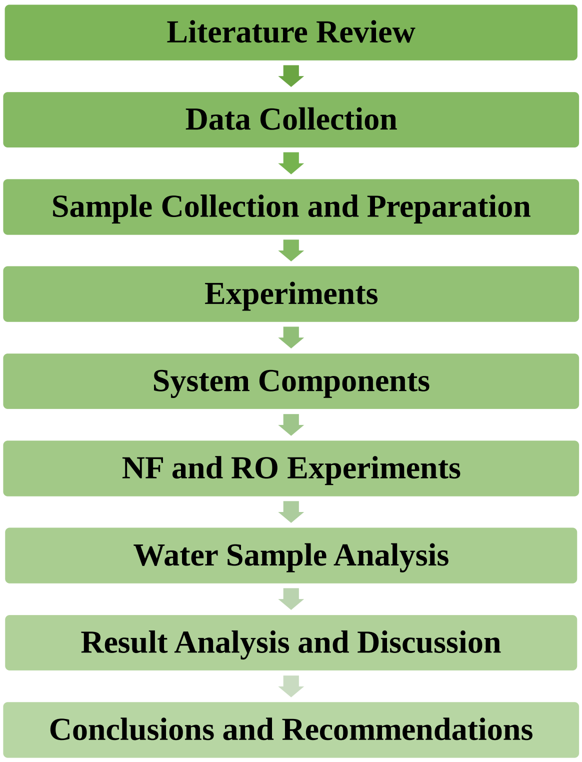


Figure (1-1): Methodology flow chart.

1.5.1 Literature Review

Revision of accessible references as books, studies and researches relative to the topic of this research which may include: Desalination Technologies, Nanofiltration, Reverse Osmoses, Membranes.

1.5.2 Data Collection

Data gathering from relevant authorities such as Coastal Municipalities Water Utility (CMWU), Palestinian water authority, Ministries and others that includes details and time series data about different parameters and elements.

1.5.3 Sample Collection and Preparation

Row seawater samples were taken from the main feed tank of Al Bassa Seawater Desalination Planet, which fed by beach well in Deir El Balah city. Samples were performed in the Public Health Lab.

1.5.4 Experiments

A pilot desalination unit were built in Abed Al Salam Yaseen company (ETA) company to run the experiments, a large range of membrane modules could be tested (NF, RO seawater and brackish water membranes) under varying operating conditions.

1.5.4.1 System Components

The system consist of (low pressure pump, high pressure pump, flow meters, temperature regulator system, house membrane, nanofiltration membrane, RO brackish water membrane, RO seawater membrane, electricity control panel, Piping system and water tanks).

1.5.4.2 NF and RO Experiments

After analyzing the row seawater samples for chemicals parameter, the experiments were carried out with deferent operating pressures and brine recirculation ratio, and measured parameters of product and brine flow at each run.

1.5.4.3 Water Sample Analysis

In each run of experiments, samples were taken; conserved and chemical analysis were performed for these samples in Public Health Lab.

1.5.5 Result Analysis and Discussion

The result that will be obtained in a series of experiments were analyzed to identify the characteristics of permeate and the parameters for the desalination process.

1.5.6 Conclusions and Recommendations

Summarizes the main findings and conclusions of this research as well as the suggested recommendations.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Water is essential to sustain life, and a satisfactory (adequate, safe and accessible) supply must be available to all. Improving access to safe drinking water can result in tangible benefits to health. Every effort should be made to achieve a drinking-water quality as safe as practicable. Safe drinking water, as defined by the World Health Organization (WHO) standard, does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages.

A desalination process separates sea or brackish water into two streams: a fresh water stream containing, a low concentration of dissolved salts and a concentrated brine stream. The desalination of water has been practiced since ancient times but was not widely used due to technological limitations, the prohibitive high capital costs, high energy consumption and finally very high unit cost when compared to conventional water. Although the desalination technologies are mature enough to be a reliable source for fresh water from the saline water, a significant amount of research and development has been carried out in order to constantly improve the technologies and reduce the cost of desalination. However, desalination projects are still not very cheap to be easily accommodated by the economics of many countries, energy consumption is still comparatively high (DACH, 2008).

2.2 Desalination

Desalination is the process of removing dissolved solids from brackish water and seawater to produce potable water. The amount of salt in water is usually described by the concentration of total dissolved solids (TDS) in the water. TDS refers to the sum of all minerals, metals, cations and anions dissolved in water. Water that contains significant amounts of dissolved salts is called saline water, and is expressed as the amount of TDS in water in mg/L. Desalination facilities exist all over the world, particularly in the eastern Mediterranean region, with use increasing on all continents. Small-scale desalination is used to supply fresh water on ships and to provide additional fresh water in some hot and arid regions (WHO, 2011).

2.3 Desalination Technologies

There are several basic techniques that can remove dissolved solids from water; distillation (evaporation and cooling), membrane separation, electrodialysis, ion exchange and eutectic freezing. Membrane separation and electrodialysis use membranes to remove minerals and dissolved solids from water. Distillation separates pure water from brackish or seawater via evaporation and condensation. Ion exchange involves the exchange of dissolved mineral ions in the water for more desirable ions by passing the water through cation and anion exchange columns. Eutectic freezing crystallization separates inorganic aqueous solutions into pure ice and solidified solutes by freezing at the eutectic point. Chemical reactions can be used by adding other chemical solutions to retentate, while calcinations can be used for the recovery of target salts. Several factors have influenced the selection of suitable salt recovery technologies, such as the composition of the feed water, target recovered salts, and other site-specific factors, such as weather and transportation (Kim, 2011). The water desalination processes require significant quantities of energy to achieve the salt separation and to get fresh water. The amount and type of the energy required differs according to the used technique (Ahmed et al., 2002). The choice of technology used for water desalination depends on a number of site specific factors, including source water quality, the intended use of the water produced, plant size, capital costs, energy costs and the potential for energy reuse (Al-Subaie et al. 2007).

2.3.1 Distillation (Evaporation and Cooling)

Salt and mineral separation from brine, seawater, or brackish water can be accomplished by distillation, in which water is vaporized from the salt solution and subsequently recovered by condensation. The various distillation processes are used to distill water and separate salt and minerals on a commercial or semi-commercial scale including multi-stage flash (MSF), multiple-effect evaporation (MEE), and vapor compression (VC). These processes operate on the principle of reducing the vapor pressure of water within the unit to permit boiling to occur at low temperatures without adding heat. In the MSF distillation, incoming feed water passing through the heating stages is heated more in the heat recovery sections of each subsequent stage. Then the water is further heated using externally supplied steam to increase the water to its highest temperature, after which the water is passed through the various stages where flashing occurs. The vapor pressure of each stage is controlled so that the water at the proper temperature and successively lower vapor pressure enters each stage to cause vaporization. The fresh water is produced by condensation of the water vapor and collected at each stage. In the MEE process, incoming feed water is heated and then passed through a series of evaporators. The produced steam is condensed on one side of a tube wall while the feed water is evaporated on the other side. The heat produced by condensing the steam was used for evaporating the feed water. Vapor compression (VC) distillation is another desalination technique, in which the heated inlet feed water passes to a brine heater, where it is heated with vapor that has been discharged by the evaporator compressor. The heated feed then passes into the evaporator, after which the generated vapor is compressed and used as the steam supply for the brine heater and the condensate is discharged as the product stream. The compressor can be connected to a flash chamber or coupled to a MEE system. In a simple solar distillation process, saline feed water is supplied continuously or intermittently to a basin of water inside a glass-covered enclosure in which water vapor rising from sun-heated brine condenses on a cooler inside the surface of the glass. The droplets of distilled water that run down the glass are then collected in troughs along the lower edges of the glass, after which the distilled water is channeled to storage tanks (Kilic et al., 2005).

2.3.2 Membrane Separation

Membranes have the ability to differentiate and selectively separate salts and water. Using this ability but differently in each case, three membrane desalination processes have been developed for desalting water: Electrodialysis (ED), reverse osmosis (RO) and nanofiltration (NF). The RO represents the fastest growing segment of the desalination market (Blank et al., 2007). Membrane technologies can be used for desalination of both seawater and brackish water, but they are more commonly used to desalinate brackish water because energy consumption is proportional to the salt content in the source water. Although thermal technologies dominated from the 1950s until recently, membrane processes now approximately equal thermal processes in global desalination capacity. Compared to thermal distillation processes, membrane technologies generally have lower capital costs and require less energy, contributing to lower operating costs. In fact, the most important progress in the area of membrane systems is the reduction of membrane cost by factor of approximately 10 over the last 30 years making the pretreatment and the seawater intake as the most expensive items of a membrane system (Khawaji et al., 2008).

2.3.2.1 Electrodialysis

Electrodialysis consists of a large number of cells alternately contained within anion-exchange and cation-exchange membranes and arranged between an anode and a cathode. Under the influence of the applied electric field, the ions migrate towards the electrodes. Because alternate membranes are permeable only to cations or anions, the water cells between the membranes are alternately depleted and enriched with salt ions. The cation membranes allow only positively charged ions to diffuse through them. Electrodialysis has been used to desalt surface and ground water since the 1950s (Allison, 1995).

2.3.2.2 Reverse Osmosis

In the reverse osmosis (RO) process, the osmotic pressure is overcome by applying external pressure higher than the osmotic pressure on the feed water. Thus, water flows in the reverse direction to the natural flow across the membrane, leaving the dissolved salts behind with an increase in salt concentration. No heating or phase change is necessary. The major energy required for desalting is for pressurizing the seawater feed. A typical large seawater RO plant consists of four major components: feed water pre-treatment, high pressure pumping, membrane separation, and permeate post-treatment (Dach, 2008).

2.3.2.3 Nanofiltration

Nanofiltration works similar to reverse osmosis expect, NF needs less pressure. This process can remove some total dissolved solids but is often used to partially soften water and is successful at removing solids and dissolved organic carbon. For low TDS brackish waters, NF may be used as a stand-alone treatment for removing salts (Dach, 2008).

2.3.3 Ion Exchange

In this process, feed water is passed through a column containing the active form of a solid cation exchanger, which is an organic resin that contains hydrogen ions and is capable of exchanging them against the positive ions contained in the feed water. The ion exchange process has been studied, investigated, and applied for desalting brackish water and recovering salts over several decades (Oztekin et al., 2007). This technique is only competitive with other desalination methods for water containing relatively low concentrations of salts due to the rising costs of resins and of treating regeneration solutions (Kim, 2011).

2.3.4 Eutectic Freezing Crystallization (EFC)

In this process, the feed is frozen continuously until the eutectic temperature is reached. Further heat removal then generates both ice and salt crystals. Specifically, ice is formed when the unsaturated solution is cooled to its freezing point, after which, the removal of additional heat induces the system to follow its freezing curve and the proportion of brine to ice decreases. At the eutectic point, ice and salt crystallize simultaneously. When compared to conventional techniques of evaporative and cooling crystallization, the advantages of EFC are that it has a low energy requirement and the theoretical possibility of complete conversion of feed into water and solidified solutes. A continuous EFC system based on direct cooling in a mixed crystallizer followed by salt–ice separation has been developed at the bench scale (Stepakoff et al., 1974).

2.4 Membrane Processes

A membrane is an interphase between two adjacent phases acting as a selective barrier, regulating the transport of substances between the two compartments. The main advantages of membrane technology as compared with other unit operations are related to this unique separation principle, i.e. the transport selectivity of the membrane. Separations with membranes do not require additives, and they can be performed isothermally at low temperatures and compared to other thermal separation processes at low energy consumption. Also, up scaling and downscaling of membrane processes as well as their integration into other separation or reaction processes are easy (Maurel, 1993). Membrane technologies have now been industrially established in impressively large scale. The markets are rather diverse, from medicine to the chemical industry, and the most important industrial market segments are medical devices and water treatment. Today, membrane technology is used in a wide range of applications and the number of applications is increasing regularly (Dach, 2008).

2.4.1 Principle

In membrane processes, a membrane separates two phases. The membrane allows transport of one or few components more readily than that of other components. The driving force for transport can be either a pressure gradient, a temperature gradient, a concentration gradient or an electrical potential gradient. A schematic representation of a membrane process is given in figure (2-1). A feed stream is divided into two streams, the concentrate stream and the permeate stream. Either the concentrate or the permeate can contain or be the desired product depending on the application (Dach, 2008).

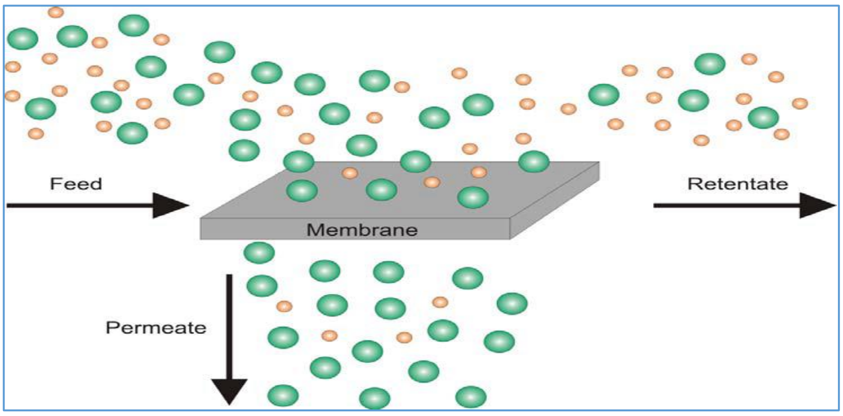


Figure (2-1): Simplified concept schematic of a membrane separation operation (Mixa et al., 2008)

The objectives of a separation can be classified roughly as follows (Maurel, 1993):

- Concentration: the desired component is present at a low concentration and solvent has to be removed
- Purification: undesirable components have to be removed
- Fractionation: a mixture must be separated into two or more desired components
- Reaction mediation: combination of chemical or biochemical reaction with membrane separation process to increase the reaction rate

The proper choice of a membrane processes should be determined by the specific application objective: particulate or dissolved solids removal, hardness reduction or ultra pure water production, removal of specific gases/chemicals etc. The end-use may also dictate selection of membranes for industries such as potable water, effluent treatment, desalination or water supply for electronics or pharmaceutical manufacturing (DACH, 2008).

2.5 Membranes Classification

Membranes can be classified according to the membrane based separation mechanisms to:

2.5.1 Membrane Based Separation Mechanisms

The membrane morphology dictates the mode of permeation and separation. The barrier structure of membranes can be classified according to their porous character table (2-1). The membrane surface can be dense selective skin, permitting only diffusive transport or a porous skin, allowing viscous flow of the permeate. The membrane separation is achieved by the manipulation of these basic morphologies. Active development is also concerned with the combination of nonporous or porous membranes with additional separation mechanisms, and the most important ones are electrochemical potentials and affinity interactions (Nguyen, 1999).

Table (2-1): Classification of membranes and membranes transfer mechanisms (Ulbricht, 2006).

Membrane barrier porosity	**Transfer mechanism**		
	Viscous flow/size exclusion	solution/diffusion	Electrochemical exclusion
Non-porous		Reverse Osmosis (RO) Pervaporation (PV) Gas separation (GS)	Electrodialysis (ED)
Microporous pore diameter dp≤2 nm	Nanofiltration (NF)	Nanofiltration (NF)	Dialysis (D)
Mesoporous pore diameter dp=2–50 nm	Ultrafiltration (UF)	Dialysis	Electrodialysis
Macro porous pore diameter dp=50–500 nm	Microfiltration (MF)		

2.5.1.1 Porous Membranes

For porous membranes, transport rate and selectivity are mainly influenced by viscous flow and sieving or size exclusion. Nevertheless, interactions of solutes with the membrane (pore) surface may significantly alter the membrane performance. An important example is the rejection of charged substances in aqueous mixtures by microporous NF membranes due to their Donnan potential. Furthermore, with meso- and macroporous membranes, selective adsorption can be used for an alternative separation mechanism, (affinity) membrane adsorbers are the most important example. In theory, porous barriers could be used for very precise continuous permselective separations based on differences in size, shape and/or functional groups (Ulbricht 2006).

2.5.1.2 Dense Membranes

For non-porous membranes, the interactions between solutes and membrane material dominate transport rate and selectivity; the transport mechanism can be described by the solution/diffusion model (Pontié, 1996).

2.5.1.3 Ion-Exchange Membranes

Ion- exchange membranes are normally of three types: (1) negatively charged membranes, (2) postively charged membranes, and (3) bipolar membranes. Two mechanisms are normally used to describe transport through charged membranes namely:

- Solution–diffusion mechanism with Donnan effect.
- Electrokinetics mechanism.

The first mechanism is based on the assumption that the membrane is nonporous, and in the second models, it is assumed that the membrane is micro-porous. Thickness of the membrane (DACH, 2008).

2.5.2 Membrane Structure

There are three classification according to the homogeneity of the pore structure along the membrane cross section into symmetric, asymmetric and composite membranes. These are represented in figure (2-2).

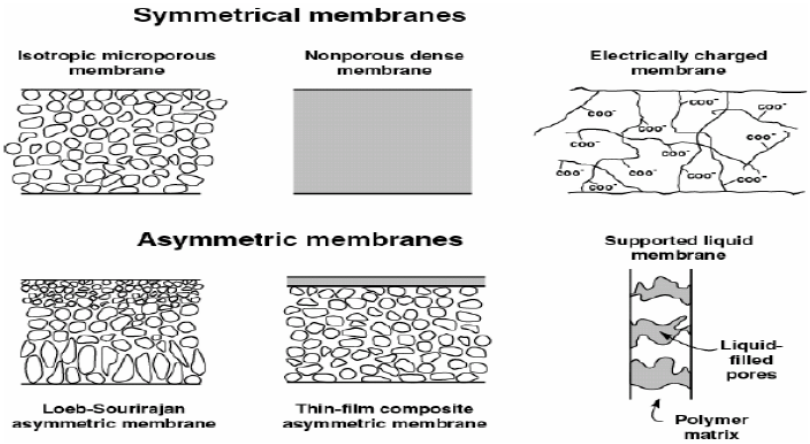


Figure (2-2): Schematic diagram of symmetric and asymmetric membrane (Cot, 1998).

2.5.2.1 Symmetric Membranes

Symmetric membranes have a homogenous pore diameter and/or pore cross section across the thickness of the membrane.

2.5.2.2 Asymmetric Membranes

In industrial applications, symmetrical membranes have been almost completely displaced by asymmetric membranes, which have much higher fluxes. An asymmetric membrane comprises a very thin (0.1-1.0 micron) skin layer on a highly porous (100-200 microns) thick substructure. The thin skin acts as the selective membrane. Its separation characteristics are determined by the nature of membrane material or pore size, and the mass transport rate is determined mainly by the skin thickness. Porous sub-layer acts as a support for the thin, fragile skin and has little effect on the separation characteristics (Maurel, 1993 and Matsuyama et al 2000). In an integral asymmetric membrane, the selective barrier layer and the microporous support always consist of the same polymer. The asymmetric membranes are prepared by the phase inversion process, which can be achieved through four principal methods: immersion precipitation, vapor-induced phase separation, thermally-induced phase separation and dry casting (Altinkaya et al., 2004).

2.5.2.3 Thin Film Composite Membranes (TFC)

Composite membranes consist of at least two layers, which differ in structure. The thin dense skin layer of a 0.01 to 0.1 µm is formed over an approximatively 100 µm thick microporous film. Composite membranes differ from asymmetric membranes by the mode of fabrication which consists of two steps: casting of the microporous support and deposition of the barrier layer on the surface of this microporous support layer (Nguyen, 1999). This preparation mode leads to significant advantages of the composite membrane compared to asymmetric membranes: (i) it improves the permeation rate which is inversely proportional to the thickness of the barrier layer and thus composite membranes shows a much higher permeation rate then asymmetric, (ii) increases the rejection rate of the membranes and (iii) minimizes the pressure drop across the membrane (Ulbricht, 2006). The materials used for the support layer and the skin layer can be different and optimized for the best combination of high water flux and low solute permeability. The TFC membrane structure is especially suitable for reverse osmosis and Nanofiltration which require high flux on one hand and high salt rejection rate on the other.

2.5.3 Membranes Materials

Membranes can be classified into organic, inorganic and hybrids of organic/inorganic materials.

2.5.3.1 Organic Membranes

Polymeric membranes account for biggest proportion of installed membranes currently in use. Several different polymers are used to suit the molecular weight cut off required, or achieve the desired resistance to fouling or performance when contacted with a specific process fluid. Organic membranes are commonly made of natural or synthetic polymer. The common materials include; cellulose acetate, polysulfone, aromatic polyamides, polyacrylonitrile (Nguyen, 1999, Suen et al., 2003 and Ulbricht 2006).

2.5.3.2 Inorganic Membranes

Membranes can also be prepared from inorganic materials such as ceramics, metals and glass. Two main classes of membranes can be distinguished: dense (they are made of metals, hybrid organic–inorganic or mixed conductive oxides) and porous (ceramic) membranes. Sol–gel processing, plasma-enhanced chemical vapor deposition and hydrothermal synthesis are methods that can be used for inorganic membrane preparation (Cot, 1998). Inorganic membranes compete with organic membranes for specific applications in drastic conditions. They can operate at elevated temperatures, with metal membranes stable at temperatures ranging from 500 – 800°C and with many ceramic membranes usable at over 1000°C. They are much more resistant to chemical attack and have long life cycle (Caroa et al., 2006). But on the other hand, their pore properties, cost, capability for surface modification may not be competitive. Accordingly, inorganic materials are infrequently adopted as the affinity membrane supports (Suen et al., 2003).

2.5.3.3 Hybrid Membranes

Organic-inorganic hybrid materials offer specific advantages for the preparation of artificial membranes exhibiting high selectivity and flux, as well as a good thermal and chemical resistance (Sforça *et al* 1999). Hybrid organic/inorganic materials are usually classified in two categories (Cot et al., 2000):

- Type I in which only interactions like van der Waals forces or hydrogen bonds exist between organic and inorganic parts. Hybrid materials can be described here as micro or nanocomposites in which one part (organic or inorganic) is dispersed in the other part acting as the host matrix.
- Type II in which covalent bonding exists between organic and inorganic parts, resulting either in an homogeneous hybrid material at the molecular level or in high surface area inorganic materials modified through surface grafting of organic groups.

2.5.4 Membrane Shapes and Module Designs

When employed for practical applications, membranes are usually housed in a module. The design of membrane module depends on the membrane shape. Various membrane shapes and module designs have been adopted in different membrane processes. The techno-economic factors for the selection, design and operation of membrane modules include cost of supporting materials and enclosure (pressure vessels), power consumption in pumping and ease of replicability (Aptel et al.,1996). Membranes are manufactured as flat sheets, hollow fibers, tubular and spiral modules. The principal advantages and disadvantages of different modules are given in table (2-2).

Table (2-2): Principal advantages and disadvantages of different modules (DACH, 2008).

Shape of module	**Tubular**	**Hollow fiber**	**Flat sheet**	**Spiral**
Packing density (m^2/m^3)	Low 10 - 300	High 9000 - 30000	Low 100 - 400	High 300 - 1000
Hydraulic diameter (mm)	5 - 15	0.1 - 1	1 - 5	0.8 -1.2
Membrane material	Inorganic Organic	Organic	Organic inorganic	Organic
Replacement of membranes	Tube	Module	Sheet	Cartridge
Risk of clogging	Low	High	Average	High
Cost	High	High	High	Low
Maintenance	Easy	Difficult	Easy	Difficult
Dead volume	High	Low	Low	Low

2.5.4.1 Tubular Module

Tubular membranes are not self-supporting membranes. They are located on the inside of a tube which is the supporting layer for the membrane. Because the location of tubular membranes is inside a tube, the flow in a tubular membrane is usually inside out. The main problem for this is that the attachment of the membrane to the supporting layer is very weak. Tubular membranes have a diameter of about 5 to 15 mm. The tubes are encased in reinforced fiberglass or enclosed inside a rigid PVC or stainless steel shell. As the feed solution flows through the membrane core, the permeate passes through the membrane and is collected in the tubular housing. Because of the size of the membrane diameter, plugging of tubular membranes is not likely to occur. This type of module can be easily cleaned. A drawback of tubular membranes is that the packing density is low, which results in high prices per module (Bouchard et al., 2000).

2.5.4.2 Hollow Fiber Module

Hollow fiber membranes are small tubular membranes with a diameter of below 2 mm. Hollow fiber membranes are self-supporting membranes. The selective barrier is sufficiently strong to resist filtration pressures. Because of this, the flow through these membranes can be either inside out or outside in (Maurel, 1993). The chances of plugging of a hollow fiber membrane are very high. The membranes can only be used for the treatment of water with low suspended solids content. The packing density of a hollow fiber membrane is very high. The cartridges contain several hundred of fibers. The key properties of efficient membrane modules are (Starthmann, 1999):

- High packing density
- Good control of concentration polarization and membrane fouling
- Low operating and maintenance costs; and
- Cost efficient production

2.5.4.3 Flat Sheet Module

The simplest device for packing flat sheet membranes is a plate-and-frame module. Plate-and frame modules can be constructed in different sizes and shapes ranging from lab-scale devices that hold single, small-size membrane coupons to full-scale systems that hold more than 1700 membranes. Two of the main limitations of plate-and-frame elements for membrane applications are lack of adequate membrane support and low packing density. Lack of adequate membrane support limits operation to low hydraulic pressure and/or operation at similar pressures on both sides of the membrane (requiring relatively high process control). Low packing density leads to a larger system footprint, higher capital costs, and higher operating costs (labor for membrane replacement). Other limitations of the plate-and-frame configuration include problems with internal and external sealing, difficulty in monitoring membrane integrity, and a limited range of operating conditions (e.g., flow velocities and pressures) (Cath et al., 2006).

2.5.4.4 Spiral Wound Module

A spiral wound module contains from one to more than 30 membranes leafs, depending on the element diameter and element type. Each leaf is made of two membrane sheets glued together back-to-back with a permeate spacer in between them (Aptel et al., 1996). A glue lines Seal the inner (permeate) side of the leaf against the outer (feed/concentrate) side. The open side of the leaf is connected to and sealed against the perforated central part of product water tube, which collect the permeate from all leaves. The leaves are rolled up with a sheet of feed spacer between each of them, which provides the channel for the feed and concentrate flow. In operation, the feed water enters the face of the element through the feed spacer channels and exits on the opposite end as concentrate**.** The construction of a spiral wound membrane element is schematically shown in figure (2-3).

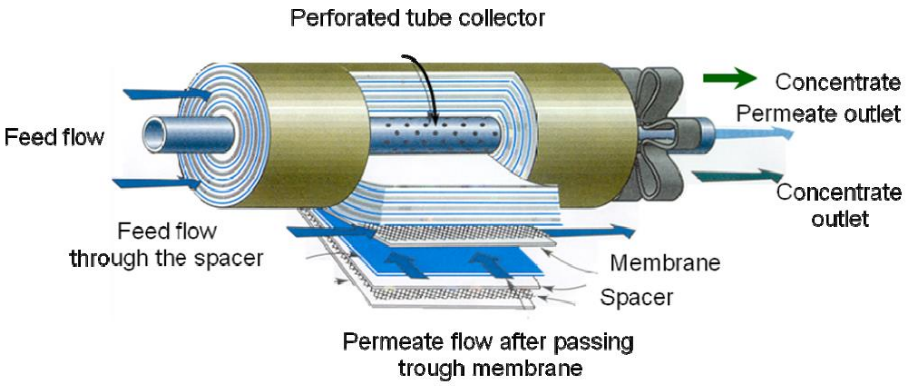


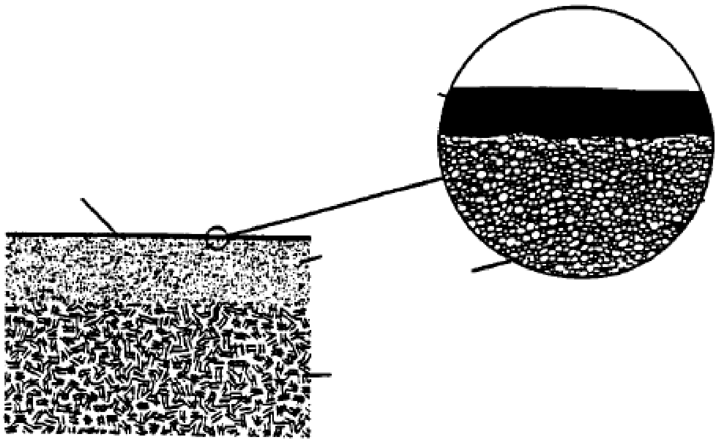
Figure (2-3): Construction of a spiral wound element (UOP, 2009).

Spiral wound designs offers many advantages compared to other module designs. Typically, a spiral wound configuration offers significantly lower replacement costs, easier maintenance, high packing density and higher pressure application. As to the possible problems for the spiral-wound design, there included difficult module cleaning, and the flow complexity caused by the decline in transmembrane pressure drop along the radial direction (Cath et al., 2006). Spiral wound configuration is the industry standard for reverse osmosis and nanofiltration membranes in water treatment.

2.6 Nanofiltration Membranes

2.6.1 NF Membrane Preparation, Structure and Properties

Various types of commercial NF membranes are available, and the separation performance of these membranes varies greatly. The two main kinds of nanofiltration membranes are asymmetric membrane and thin film composite membrane. The latter shows higher water permeability and salt rejection because it consists of a dense (dp < 2 nm), ultra-thin selective layer on the surface of a porous substrate (Yang et al., 2007). Figure (2-4) shows a schematic of this type of membrane.



Polyamide, Microporous Polysulfone, Polyester Support Web, Ultrathin Barrier Layer 0.2 micro-m, 40 micro-m, 120 micro-m.

Figure (2-4): Schematic diagram of the thin film composite membranes (FILMTEC™ Membranes, 2012**).**

It is well known that there are many methods to prepare composite membrane. NF membranes are manufactured using two preparation techniques:

- Polymer phase inversion resulting in a homogeneous asymmetric membrane.
- Interfacial polarisation of a thin film composite layer on top of a substrate ultrafiltration membrane or other porous substrate.

Cellulose acetate and sulfonated polysulfone are two common materials used for making homogeneous asymmetric NF membranes. Thin film composite NF membranes use cross linked polyamide polymers, reacted to carboxylic group or other charged groups. Substrate materials commonly used for thin film composite membranes are polysulfone (PS), polyethersulfone (PES), polyvinyledene fluoride (PVDF), polyacrylonitrile (PAN), and Polyether ether Ketone (PEEK). Nowadays, Most NF membranes are packed into spiral wound elements; however, tubular, hollow fiber and flat sheet/plate and frame modules are also available. One of the main uses of spiral wound membranes is in water treatment for drinking water production (Ben Farès, 2006).

2.6.2 Nanofiltration Membranes Available in the Market

Several NF membranes are available in the market. Presently, NF membranes are commercially supplied by many companies table (2-3). Nanofiltration membranes are a relatively recent development in the field of RO membrane separations. Thus, the research efforts on reverse osmosis and the fast growing of RO technology in the market have had an impact on all of the progress in nanofiltration technology.

Table (2-3): Main manufacturers of nanofiltration membranes (Ben Farès, 2006).

Manufacturer	Material	Configuration
Advance Membrane Technology (United States)	PSSf	Spiral
Celfa-Daicel (Suisse)	CA or PA	Flat sheet
Dow chemical (Denmark)	PA	Spiral
Filmtec (United States)	Diverse	Diverse
UOP fluid system (United States)	CA-PA	Spiral
Hoechst (Germany)	CA-PES	Flat sheet /spiral
Hydranautics (United States)	Composite	Spiral
Kalle (Germany)	CA-PA	Plat/Spiral
Koch membrane systems (Germany)	Diverse	Diverse
Membrany (Russia)	Diverse	Diverse
Millipore (United States)	PA	Plat/spiral
Nitto-Denko (Nitto Electrical Industriel) (Japan)	PVA-PSf	Diverse
North Carolina SRT (United states)	Diverse	Plat
NWW acumen (United states)	PS	Spiral
Osmonics Desalination Systems (United states)	CA-PA	Spiral
Osmota (Germany)	Composite	Diverse
PCI (Paterson Candy International) (Great Britain)	Diverse ceramic polymers	Tubular
Stork Friesland (Canada)	PA	Tubular
Orelis (France)	Zircon	Diverse
Tami (France)	Ceramic	Tubular
Toray (Japan)	PA-PES	Spiral
Tri-Sep (United states)	PA	spiral
US Filter SCT (United states, France)	Titan	Tubular
Wheelabrator (United states)	PVDf-PS-PAN	Tubular
X-Flow (Nederland)	PES	Spiral

Polysulfone (PSF), polyether sulfone (PES), polyvinyledene fluoride (PVDF), polyacrylonitrile (PAN), Polyamide (PA), Polysulfone sulfonated (PSSf), Polyvinyl alcohol (PVA).

2.6.3 Applications of NF Membranes

From the very start, the drinking water industry has been the major application area for nanofiltration. The historical reason for this is that NF membranes were essentially developed for softening, and to this date NF membranes are still sometimes denoted as ‘‘softening’’ membranes (Van der Bruggen and Vandecasteele, 2003). The first nanofiltration plants that were developed were essentially meant for softening, and NF became a concurrent to lime softening. Softening was mainly of interest for groundwater in contrast to surface waters, where the major problem is usually a high organic content. At the present time, nanofiltration is rather seen as a combinatory process capable of removing hardness and a wide range of other components in one step (Schaep, 1998). The possibility of replacing many different treatment processes by a single membrane treatment was the engine for intense research and an enhanced interest from drinking water companies. Due to their unique separation properties, NF membranes are widely used in industry. It is advantageous to use NF membranes when (Rautenbach and Groschel, 1990):

- It is not necessary to retain monovalent salts.
- A separation of anions of different valency must be achieved.
- A separation between low molecular weight organic material and a monovalent salt is desired: i.e. separation of lactose from ash; separation of dyes from sodium chloride.
- Purification of acids, bases or solvent is being investigated: especially when the contaminants are in the NF MWCO range.
- A reduction in osmotic pressure is required: compared to reverse osmosis membranes.

NF membranes are applied in a variety of industrial applications. NF membranes extremely useful in the fractionation and selective removal of solutes from complex process streams. This development of NF technology as a viable process over recent years has led to a marked increase in its adoption in a number of industries such as treatment of pulp-bleaching effluents from the textile industry (Rosa and de Pinho, 1995, Bes-Pia et al., 2005, Gozalvez-Zafrilla et al., 2008).

2.6.4 Membrane Performance

2.6.4.1 Pure Water Permeability

Pure water flux through a membrane can be described by the Darcy's law from the eq. (2-1):

$$Jv = Lp\ \Delta P \qquad (2\text{-}1)$$

Where :

Jv: Pure water flux.

Lp:The hydraulic permeability.

ΔP: change in pressure.

The pure water permeability reflects the porous structure of the membrane. A constant value of pure water permeability, i.e. the linear dependence of the pure water flux Jv on pressure, points to unchangeable membrane porosity. If the water flux dependence on pressure deviates from linearity, the pure water permeability of a membrane is not constant, and it indicates the changes in the membrane's porous structure (Kosutic et al. 2006). Thus, by measuring a dependence of the membrane's pure water permeability on pressure, a state of the membrane's active layer porosity can be characterized. Reported that in the case of the loose NF membranes, containing in addition to medium size pores a remarkable fraction of large pores, the water flux is prevailingly determined by the large pores. The large pores shrink under pressure only slightly resulting in a minor water flux drop. The pressure effect is the strongest for the tight NF membranes, which active layer accomodates many medium sized pores. The increased pressure appreciably reduces both the dimensions of the medium sized pores and the water flux. The active layer structure of the RO membranes is fairly compact containing numerous very narrow pores. Their size cannot be reduced under pressure significantly due to the resistance of the already shrunk solid polymer matrix. The results would be small water flux changes and low susceptibility parameter of these membranes. However, it has been also shown that the water flux at higher pressures can be increased due to opening up a number of closed pores to become "active" ones, i.e. by increasing the effective number of pores (DACH, 2008).

2.6.4.2 Rejection Characteristics

parameter frequently used to describe the rejection characteristics of a membrane is the desalting degree. The desalting degree of a membrane is commonly reported as the percent rejection of electrolytes such as sodium Chloride, magnesium sulfate and other electrolytes. The desalting degree can be useful parameter in estimating the rejection of some compounds. This parameter is needed to be considered during membrane selection. Many authors have used this parameter to determine the effect of preparation condition on NF membranes performance (Sun et al., 2008, 2006, Van Gestel et al., 2002, Yang et al., 2007). Some authors used the membrane permeation tests and the sequence of salt rejection to evaluate the membrane charge (Labez et al., 2003, Krieg et al., 2004, Schaep et al., 2001, Wang, 2005). Membrane rejection (R) is calculated by the following relation:

$$R(\%) = (1 - \frac{Cp}{Co}) \times 100 \qquad (2\text{-}2)$$

Where C_p and C_o are the salt concentrations in the permeate and in the feed solution respectively.

2.6.5 Parameters Affecting the Performance of NF Membranes

When designing a NF process, one should consider several operating parameters. Many authors (Ben Farès et al., 2006, Bellona et al., 2004), have studied the influence of operating conditions on NF membranes performance. The most important operating parameters affecting the performance of NF membranes are similar to those for most crossflow filtration processes.

2.6.5.1 Pressure

Pressure difference is the driving force responsible for a NF process. The effective driving pressure is the supplied hydraulic pressure less the osmotic pressure applied on the membrane by the solutes. NF provides good separation at net pressures of 10 bar or higher (DACH, 2008).

2.6.5.2 Temperature

Increasing the process temperature increases the NF membrane flux due to viscosity reduction. Additionnaly, increasing temperature increases mean pore radii and the molecular weight cut off suggesting changes in the structure and morphology of the polymer matrix comprissing the membrane barrier layer (Ramesh et al 2003). The rejection of NF membranes is not dependent significantly on the process temperature.

2.6.5.3 Crossflow Velocity

Increasing the crossflow velocity in an NF membrane process increases the average flux due to efficient removal of fouling layer from the membrane surface. However, the mechanical strength of the membrane, and construction of the element and system hardware will determine the maximum crossflow velocity that can be applied. Running a NF membrane at too high crossflow velocity may cause premature failure of membranes and modules. Increasing cross flow velocity also increase the pressure drop (DACH, 2008).

2.6.5.4 Recovery Rate

Many authors have reported that an increase of feed water recovery leads to a decrease in rejection (Bannoud. 2001, Lhassani et al., 2001, Abouzaid et al., 2003). A study by Chellam and Taylor, reported that feed water recovery had a significant impact upon the rejection of total hardness. These findings indicate that diffusion across the membrane which is one of the main driving factors for solute permeation becomes higher when increasing the recovery rate. This increase may, be responsible for stronger concentration–polarisation, membrane–solute interactions and, even, solute adsorption onto membrane surface, all of these phenomena with a deleterious effect on the membrane performance.

2.6.5.5 pH

The pH affects performance of NF membranes in more than one way. The charged sites on the NF membrane surface (i.e. carboxylic group, sulfonic group) are negatively charged at neutral pH or higher, but lose their charge at acidic ph. It is well known that most NF and RO membranes have lower rejection at low pH, or after acid rinse. It should be noted, however, that since different membrane manufacturers use different chemistries to produce their thin film composite layer, the pH dependency of a membrane should be determined for each membrane type. In addition to the effect of pH on the membrane itself, pH can be responsible for changes in the feed solution, causing changes in membrane performance. Two examples are change of solubility of ions at different pH regimes, causing different rejection rate; and change in the dissociation state of ions at different pH ranges (Teixeira et al., 2005, Bellona et al., 2004).

2.7 NF Versus RO Membrane

The term, nanofiltration“ signifies that particles of Nano metric dimensions are separated through the NF membranes. NF membranes have low molecular weight cut-offs (200 - 1000 Da) and smaller pore size (~1 nm). Therefore, the separation of components with these molecular weights from higher molecular weight components can be accomplished (Timmer, Johannes M.K. 2001). They also have a surface electrostatic charge which gives them great selectivity towards ions or charged molecules. More specifically, NF membrane can be used to remove small neutral organic molecules while surface electrostatic properties allowed monovalent ions to be reasonably well transmitted with multivalent ions mostly retained (Bowen and Welfoot, 2002). NF offers several advantages, such as low operation pressure, high flux, high retention of multivalent anion salt and organic molecular above 300, relatively low investment, low operation and maintenance cost. By the second half of the eighties, nanofiltration had become established, and the first applications were reported table (2-4) shows the advantages and disadvantages of the NF system (Conlon and McClellan, 1989) A nanofiltration (NF) membrane works similar to reverse osmosis except that with NF, less pressure is needed (70 and 140 psi) because of larger membrane pore size (0.05 µm to 0.005 µm). Nanofiltration can remove some total dissolved solids, but is often used to partially soften water and is successful at removing solids, as well as dissolved organic carbon. For low TDS brackish waters, NF may be used as a standalone treatment for removing salts (Younos and Tulou, 2005). Nanofiltration (NF) membranes have lower rejection of monovalent ions when compared to RO membranes specifically designed for nitrate (MWH, 2005; Bellona. et al., 2008).

CHAPTER THREE: STUDY AREA

3.1 Location

Gaza Strip is located in a semi-arid area with scarce water resources. It is a part of the Palestinian coastal plain in the south west of Palestine as shown in figure (1-1), where it forms a long and narrow rectangular area of about 386 km^2, with 45 km length, and between 5 and 12 km width. Nowadays, its five governorates are: Northern, Gaza, Middle, Khanyounis and Rafah. It is located on the south-eastern coast of the Mediterranean Sea, between longitudes 34° 2" and 34° 25" east, and latitudes 31° 16" and 31° 45" north. The Gaza Strip is confined between the Mediterranean Sea in the west, Egypt in the south (UNEP, 2003).

Figure (3-1): Gaza Strip Map (Wikipedia, 2009)**.**

3.2 Current Water Situation in Gaza Strip

Gaza strip is considered one of the most water scarce places in the world, where the main source is the ground aquifer. The water situation is disastrous due to the deficit on either water quality or quantities due to many reasons such as rainfall scarcity, continuous urbanization with limited land area, and population increase, which all leads to a critical situation.

3.3 Water Resources in Gaza Strip

Gaza's water resources are essentially limited to that part of the coastal aquifer that underlies its 365 km^2 area. The coastal aquifer of Gaza strip is part of regional ground water system that stretches from the coastal areas of the Sinai in the south to Haifa in the north. There is no other surface water or springs existed in the strip and could be used as reliable source (PWA, 2000). The coastal aquifer holds approximately 5000 MCM of groundwater of different quality. However, only 1400 MCM of this is fresh water, with chloride content of less than 500 mg/l. This fresh groundwater typically occurs in the form of lenses that float on the top of the brackish and/or saline groundwater. That means that approximately 70% of the aquifer is brackish or saline water and only 30% is fresh water (Al-Yaqubi A., et al., 2007). The aquifer has 10-15 km wide. The aquifer consists primarily of Pleistocene age Kurkar Group deposits including calcareous and silty sandstones, silts, clays, unconsolidated sands and conglomerates (PWA, 2000). The aquifer is varied in depth, thickness and type. The maximum aquifer thickness is 160 m in the North and decrease to 70 m in the south of the strip. The base of coastal aquifer system is formed of impervious clay shade rocks of Neogene age (Saqiyah formation) (MOP, 2010).

3.4 Water Quality

Groundwater quality mainly represented according to Chloride and Nitrate concentrations, since these parameters potentially contributing to salinity and pollution. At present an about 90% of the domestic water pumped from the aquifer is far from the WHO standard in terms of Chloride and Nitrate concentrations (PWA, 2012). Ongoing deterioration of the water supply of Gaza Strip poses a major challenge for water planners and sustainable management of the coastal aquifer. The aquifer is presently being overexploited, with total pumping exceeding total recharge. In addition, anthropogenic sources of pollution threaten the water supplies in major urban centers. Many water quality parameters presently exceed World Health Organization (WHO) drinking water standards. The major documented water quality problems are elevated chloride (salinity) and nitrate concentrations in the aquifer (Aish, 2004). Table (3-1) shows the water quality in the different governorates of the Gaza Strip according to the concentration of

NO3, TDS and Cl respectively. Nitrate concentration ranges from 4 ppm to 496 ppm, total dissolved solids ranges from 381 ppm to 20000 ppm and chloride concentration ranges from 84 ppm to 11289 ppm. Therefore, the most serious water problems in the Gaza Strip are the shortage and contamination of the groundwater. One of the major options for solving the water problems is the utilization of desalination technology for both sea and brackish.

Table (3-1): Water quality in the Gaza governorates regarding NO_3, TDS and Cl^- concentrations (PWA chemical test, 2013).

Water Quality	NO_3 (ppm)		TDS (ppm)		CL^- (ppm)	
	Range	Mean	Range	Mean	Range	Mean
North Gaza	37-254	111.5	452-5003	2334	85-2592	982.9
Gaza	4-253	115	452-5003	2343	724- 11289	965
Middle Gaza	16.7-496	124	53-10695	2662	206-5325	1116
Khan Younis	49.3-357	116	381- 9300	2367	84-4473	981
Rafah	9.5-289.9	114.8	198-3472	2315	9.5-289.9	967

3.5 Desalination Situation in Gaza Strip

Table (3-2) lists all the currently operated desalination plants in the Gaza Strip. The PWA constructed some other plants in cooperation with different municipalities in addition to dozens of small commercial desalination units.

Table (3-2): Desalination plants in Gaza Strip (Mogheir et al. 2013).

Area	Location	Date of construction	Capacity (m^3/hr)	Production (m^3/day)	Recovery rate %	Energy consumption (kWh)	Cost of 1 m^3 ($)
Al – Balad	Deir El-Balah	1993	60	420	75	120	0.72
Al– Sharqia	K.Younis	1997	55	440	70	60	0.31
Al-Saada	K.Younis	1998	80	640	70	60	0.34
Al-Bureij	Al-Bureij	2009	60	480	83	60	0.28
Al- Nuwairi	B.Suhaila	2010	50	400	75	60	0.34
Al-Salam	Rafah	2010	60	480	80	60	0.27

All membranes of these plants are RO made by Koch Company – USA.

The municipality of Dier Albalah operates the plant with a maximum capacity of 1872 m^3/d. This RO plant uses brackish groundwater as influent to product 1080 m^3/d desalinated water with a recovery rate of 75%. There are two RO desalination plants located in Khan Yunis City: El-Sharqi, built in 1997, and Al-Saada, built in 1998. Both are owned and operated by the PWA and Khan Yunis Municipality. The capacity of the El-Sharqi plant is 1200 m^3/d and the capacity of the Al-Saada plant is 1560 m^3/d. In the Gaza industrial zone, a RO desalination plant was built in 1998. It uses brackish groundwater as influent and has a capacity of 1080 m^3/d. It is planned that the desalinated water from this plant will be used for industrial purposes in the area and partially for municipal use in the neighborhood. However, due to the political situation, the work in this plant was banned (Baalousha et al. 2006). There are also two plants that use seawater as influent. The first one is located in the northern part of the Gaza Strip directly at the beach and uses saline water from beach well as a feed. Productivity of this plant is 1200 m^3/d in the first phase and 5000 m^3/d in the final phase. This plant is not yet completed because of the political situation. The second RO desalination plant is located in the middle area of the Gaza Strip with a capacity of 600 m^3/d in the first phase, and 2600 m^3/d in the second phase. Influent of this plant is saline water from wells drilled directly at the beach. There is a plan for a regional desalination plant for the Gaza Strip with a capacity of 60,000 m^3/d in the first phase and 150,000 m^3/d in the second phase (El Sheikh, et al. 2003, El Sheikh, 2004). This plant will meet partially the increasing demand of water supply in the area for different purposes. Seawater will be used as a feed for this plant (direct intake). There are others owned and operated by the private sector under the control of the PWA and the Ministry of Health. All these plants use RO technology to desalinate brackish groundwater and the treated water is sold. Nowadays, there are much private desalination plants owned and operated by private investors. The capacity of these plants varies between 20 to 150 m^3/d (Jaber, et al. 2004).

CHAPTER FOUR: MARERIALS AND METHODS

4.1 General

Across flow pilot scale desalination unit was built to run the experiments for research purpose in which a large range of membrane modules could be tested (NF, RO seawater and RO brackish water membranes) under varying operating conditions. A series of experiments were carried out under varied applied pressure, flowrate from the feed water tank and flow rate from brine recirculation to obtain details of the experimental tests. Details about the used materials and methods are listed below:

4.2 Materials

4.2.1 Membranes

Three types of spiral wound modules of (2.5") including nanofiltration membrane (NF90-2540), RO seawater membrane (SW30-2540) and RO brackish water membrane (BW-2540) were used. These membranes were purchased from DOW and Toray companies by ETA company. Table (4-1) shows the commercial names of the membranes and their supplier.

Table (4-1): Names and supplier of used membranes

Membrane type	Membrane Name	Manufacturer
NF membranes	NF90-2540	Dow – Filmtec (USA)
Seawater RO membrane	SW30-2540	Dow – Filmtec (USA)
Brackish water RO membrane	BW-2540	Toray (Japan)

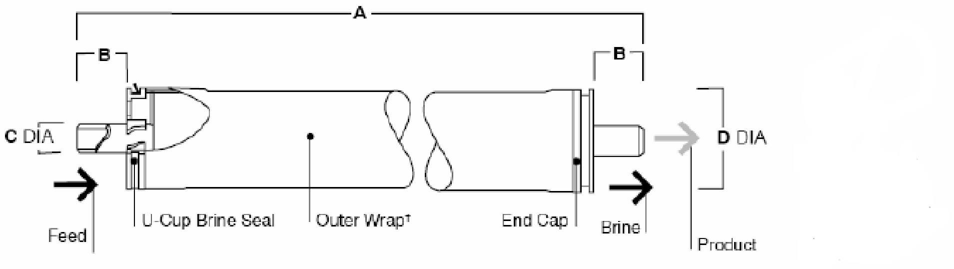
All used membranes are polyamide thin film composite membranes.

Pictures of used membranes are shown in figure (4-1).

Figure (4-1): Pictures of NF90-2540, BW-2540 and SW-2540 membranes respectively

4.2.1.1 NF 90-2540 Membrane

The NF90 membrane elements is high salt removal (90%), high iron removal, pesticide, herbicide removal and TOC removal, see figure (4-2).



Product	Single Element Recorery	Dimensions – Inches (mm) A	B	C	D
2540 Configuration[5]	15%	40 (1,016)	1.19 (30)	0.75 (19)	2.401 (61)
4040 Configuration[6]	15%	40 (1,016)	1.05 (27)	0.75 (19)	3.913 (99.4)

4. Consult the most recent Design Guidelines for multiple element applications and recommended element recovery rates for various feed sources. 1 inch = 25.4 mm
5. Element to fit 2.45-inch (62 mm) I.D. pressure vessel.
6. Element to fit 4.00-inch (102 mm) I.D. pressure vessel.

† Tape outer wrap for 2540 configuration and fiberglass outer wrap for 4040 configuration.

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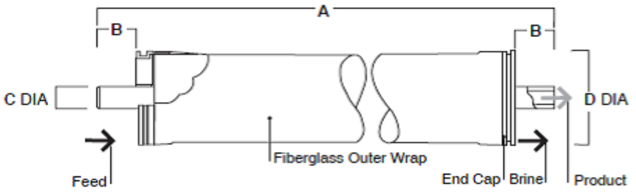
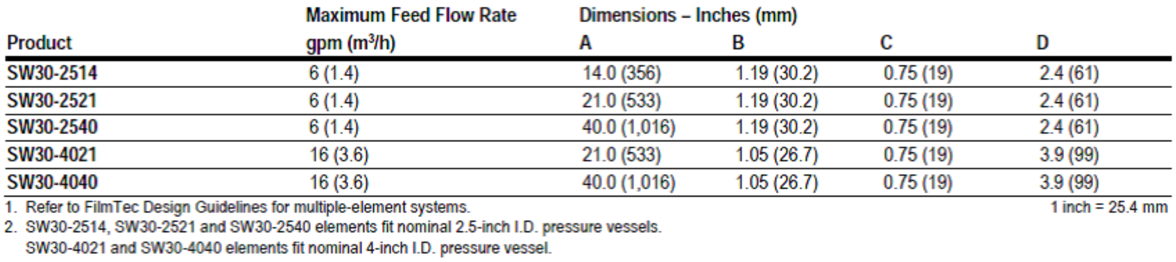
Figure (4-2): NF90-2540 membrane detailed (FILMTEC™ Membranes).

4.2.1.2 SW 30-2540 Membrane

This membrane is an efficient membrane that it sustains a high productivity while maintaining an excellent salt rejection under high flow rates of both sea-based and land- based desalinators. See figure (4-3).





Product	Maximum Feed Flow Rate gpm (m^3/h)	Dimensions – Inches (mm) A	B	C	D
SW30-2514	6 (1.4)	14.0 (356)	1.19 (30.2)	0.75 (19)	2.4 (61)
SW30-2521	6 (1.4)	21.0 (533)	1.19 (30.2)	0.75 (19)	2.4 (61)
SW30-2540	6 (1.4)	40.0 (1,016)	1.19 (30.2)	0.75 (19)	2.4 (61)
SW30-4021	16 (3.6)	21.0 (533)	1.05 (26.7)	0.75 (19)	3.9 (99)
SW30-4040	16 (3.6)	40.0 (1,016)	1.05 (26.7)	0.75 (19)	3.9 (99)

1. Refer to FilmTec Design Guidelines for multiple-element systems.
2. SW30-2514, SW30-2521 and SW30-2540 elements fit nominal 2.5-inch I.D. pressure vessels.
   SW30-4021 and SW30-4040 elements fit nominal 4-inch I.D. pressure vessel.

1 inch = 25.4 mm

Figure (4-3): SW30-2540 membrane detailed (FILMTEC™ Membranes)**.**

4.2.1.3 BW- 2540 Membrane

The Toray BW 30-2540 membrane elements is also high salt removal (99%), high iron removal, pesticide, herbicide removal and TOC removal. Data about maximum pressure, maximum temperature and salt rejection were provided by the suppliers and shown in table (4-2).

Table (4.2): Characteristics of membranes as provided by the suppliers (FILMTEC™ Membranes **and Toray™).**

Membrane	Manufacturer	Geometrical area (m^2)	Maximum operating pressure (bar)	Maximum feed flow m^3/hr	pH range	T°C max	Permeate flow rate (m^3/d)	Stabilized salt rejection (%)
NF90-2540⁽¹⁾	Dow – Filmtec (USA)	2.6	41	1.4	2-11	45	2.1	90
SW30-2540⁽²⁾	Dow – Filmtec (USA)	2.8	69	1.4	2-11	45	2.6	99.4
BW-2540	Toray (Japan)	2.6	41	1.4	2-11	45	2.1	99.7

(1) Permeate flow and salt rejection based on the following test conditions: 500 ppm $CaCl_2$, 70 psi (0.5 MPa), 77°F (25°C) and 15% recovery.
2,000 ppm NaCl, 70 psi (0.5 MPa), 77°F (25°C) and recovery as indicated below
Flow rates for individual elements may vary +/- 25%.
(2) Permeate flow and salt rejection based on the following test conditions: 32,000 ppm NaCl, pressure specified above, 77°F (25°C) and the recovery rates; SW30-2540 – 8%.
Permeate flows for individual elements may vary +/-20%.

4.2.2 Chemicals

Sodium chloride NaCl of a 99% purity was used to prepare salt solutions of (2000, 7109, 32000 and 32560) ppm.

4.2.3 Deionized Water Preparation

Deionized water obtained from Abdul Salam Yaseen Company for water desalination plants and purification systems (ETA), located in Gaza city, were used to prepare the salt solutions.

4.2.4 Seawater

Row seawater were obtained from the main feed tank of Al Bassa Seawater Desalination Plant which is fed by a beach well in Deir El Balah city. Raw seawater sample were sent to the Public Health Lab. and analyzed for different parameters as shown in table (4-3).

Table (4-3): Chemical tests results of row seawater (Jan. 2015).

Test	Unit	Result
pH		7.13
E.C	Micro mho/cm	59,000
TDS	ppm	36,580
Nitrate	ppm as NO_3^-	8.19
Chloride	ppm as Cl^-	20,798.8
Sulfate	ppm as SO_4^{--}	2,958.34
Alkalinity	ppm as CO_3^{--}	118.65
Hardness	ppm as $CaCO_3$	7,183.90
Calcium	ppm as Ca^{++}	481.40
Magnesium	ppm as Mg^{++}	1,451.55
Potassium	ppm as K^+	444.78
Sodium	ppm as Na^+	12,800
Cadmium	µg/L as Cd	116
Copper	µg/L as Cu	326
Lead	µg/L as Pb	210

4.2.5 Experimental Apparatus

The experimental apparatus was composed of the following:

4.2.5.1 Pilot Scale Testing Unit

The pilot scale testing unit was built at ETA company. This pilot unit was designed to test a wide range of membrane modules under varied operating conditions. The pilot unit was mounted on a skid that has dimensions of (L = 150 cm, W = 180) cm and H = 220 cm. Pictures of the pilot unit is shown in figure (4-4).

Figure (4-4): Pictures of the pilot unit

The pilot unit consists of:

- Electrical control panel was used to control the system.
- Low pressure centrifugal pump (1HP) was used as a feed pump.
- 1µm cartridge filter was used to avoid the carryover of large debris into the membrane system.
- Temperature regulating system to adjust the temperature of the feed water (chilling only).
- High pressure pump NMT1820 (3HP) of 18 L/min flow rate, maximum pressure 200 bar, 9.2 HP and 6.8 Kw was used to generate the needed pressure.
- Pressure vessel housing of standard 2.5" membrane module.
- Pressure gauges to measure the operating pressure.
- Flow meter to measure the flow rate of the concentrated and product water.
- Thermometer to measure the temperature of feed water.
- Pipes: PVC pipes and high pressure pipes were used to connect the parts of desalination unite.
- Manual regulation valve was fitted on the concentrate line to control the feed pressure
- An internal concentrate recirculation loop fitted with a manual regulation valve.
- An external concentrate recirculation loop fitted with a manual regulation valve.

- An external permeate recirculation loop to allow recycle permeate into the feed water tank.
- Water tanks with (500 L and 250 L) volume capacity.

The experimental apparatus pictures are shown in the figure (4-5).

Figure (4-5): Pictures of experimental apparatus

4.3 Methods

3.3.1 Measurements and Analytical Method

Samples of permeate water from each experiment were collected. Chemical analysis of permeate water was carried out at general public health lab. Analyzed parameters, unit, method and used equipment for each parameter are shown in table (4-4).

Table (4-4): Analyzed parameters, unit, method and used instruments (Lenore, Arnold et al. 1998)

Test	Unit	Method*	Instrument
pH		pH meter (4500H^+ B)	JENWAY pH meter 3310
E.C	MS/cm	E.C. meter (2520 B)	Conductivity meter SENE Ion7 (Hach)
TDS	mg/l	E.C. meter (2540 C)	Conductivity meter SENE Ion7 (Hach)
Nitrate	Mg/l as NO_3^-	U.V. spectrophotometric (4500-$NO3^-$ B)	JENWAY 6305 Spectrophotometer
Chloride	Mg/l as Cl^-	Titrimetric AgNO3 method (4500 Cl^- B)	
Sulfate	mg/l as SO_4^{--}	Turbidimetric method (4500 (SO_4^{--} 2 E)	HACH 2100 Turbidity meter
Alkalinity	mg/l as CO_3^{--}	Titrimetric method (2320 B)	
Hardness	mg/l as $CaCO_3$	Titrimetric method (2340 C)	
Calcium	mg/l as Ca^{++}	Titrimetric method (3500 Ca^{++} B)	
Magnesium	mg/l as Mg^{++}	Calculation method (3500 Mg^{++} B)	
Potassium	mg/l as K^+	Flame emission photometric (3500 K^+ B)	Flame photometer 410
Sodium	mg/l as Na^+	Flame emission photometric (3500-Na^+ B)	Flame photometer 410
Cadmium (total)	µg/L as Cd	Flame atomic absorption method (3111 B)	UNICAM 929 AA Spectrometer
Copper (total)	µg/L as Cu	Flame atomic absorption method (3111 B)	UNICAM 929 AA Spectrometer
Lead (total)	µg/L as Pb	Flame atomic absorption method (3111 B)	UNICAM 929 AA Spectrometer

* Method described in Standard Methods for the examination of water and wastewater

Water samples were collected and stored in polyethylene bottles. The samples were preserved by lowering the pH to 2 via adding one ml of concentrated nitric acid to each bottle. For heavy metals analysis, samples were digested and concentrated according to the method no 3030 D. described in Standard Methods for the examination of water and wastewater.

4.3.2 Calculated Parameters

The following parameters were calculated:

4.3.2.1 Volumetric Flux (Jv)

Volumetric flux were determined by substituting the permeate flow rate value in eq. (4-3).

$$Jv = \frac{Qp}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4-3)}$$

Where:

Jv: water flux (L/hr.m^2).

Q_p: permeate flow (L/hr).

A: the membrane surface area (m^2).

4.3.2.2 Hydraulic Permeability (Lp)

The hydraulic permeability is obtained from the slope of the plot of flux (Jv) versus the increasing trans membrane pressure. The intercept on x-axis of the plot gives the critical pressure when the transmembrane pressure is equal to the osmotic pressure.

4.3.2.3 Transmembrane Pressure

Transmembrane pressure is calculated using equation (4-4).

$$\Delta P = \frac{Pf+Pc}{2} - Pp \ldots\ldots\ldots\ldots\ldots\ldots \text{(4-4)}$$

Where:

ΔP: the transmembrane pressure in bar.

Pf: Feed pressure.

Pc: Concentrate pressure.

Pp: Permeate pressure.

4.3.2.4 Recovery Rate

Recovery rate is calculated using equation (3-5).

$$Y = \frac{Qp}{Qf} * 100\% \quad \ldots. \text{(4-5)}$$

Where:

Y: recovery rate.

Q_p: permeate flow rate.

Q_f : feed flow rate.

4.3.2.5 Rejection Rate

Rejection rate is one of the most important characteristics of the membrane. It has the same meaning of removal efficiency that it represents the ability of membrane to reject salts and impurities from feed water. Rejection rate depends on the feed water characteristics, membrane characteristics and applied pressure. Rejection rate was measured using equation (4-6).

$$R = (1 - \frac{Cp}{Co}) \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4-6)}$$

Where:

R: Rejection rate (%)

C_p: Salt concentration in permeate (mg/l).

C_f: Salt concentration in feed water (mg/l).

4.3.2.6 Specific Energy Consumption (SEC)

SEC for one permeate cubic meter is proportional to the transmembrane pressure. It is calculated by the equation (4-7).

$$SEC = \frac{\Delta P}{\eta . Y} * \frac{100}{36} \ldots \ldots \ldots \ldots . . (4-7)$$

Where:

SEC: Specific Energy Consumption in (kWh/m^3)..

ΔP: the transmembrane pressure in bar.

η: the global pumping system efficiency.

Y: the recovery rate.

4.3.3 Experimental Program

In this search, as shown in figure (4-6) the desalination unit were designed and built to be operated *with and without internal brine recirculation* under the following modes.

I- No Brine Recirculation Mode

- The manual regulation valve V1 in internal concentrate loop is closed.
- The manual regulation valve V2 in external concentrate loop is open.
- The manual regulation valve V3 in external permeate loop is open.
- The recovery rate is the ratio of the permeate flow rate to the flow rate through the booster pump (same flow rate as the one through the high pressure pump and the same flow rate from feed tank).

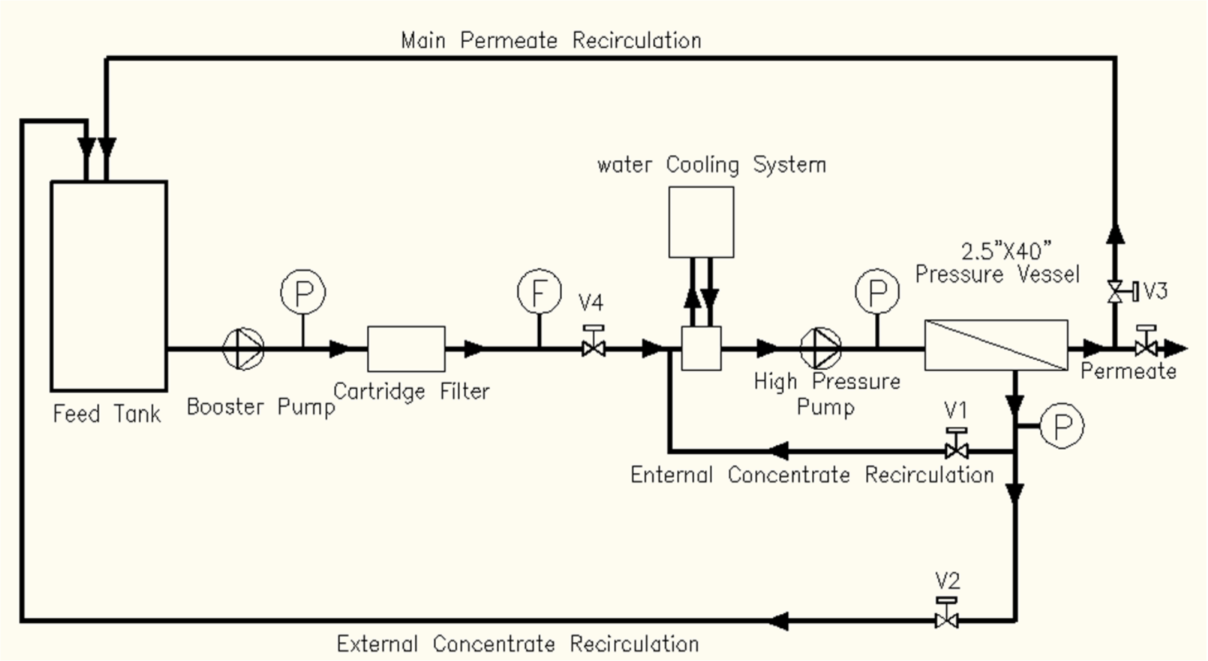


Figure (4-6): Process flow sheet of the skid-mounted unit

II- Internal Brine Recirculation Mode

- The manual regulation valve V1 in internal concentrate loop is partially open.
- The manual regulation valve V2 in external concentrate loop is partially open.
- The manual regulation valve V3 in external permeate loop is open.
- A portion of the concentrate is directly recirculated downstream through the cartridge filters.
- The recovery rate is the ratio of the permeate flow rate to the flow rate through the booster pump (same flow rate from feed tank).
- The recirculation rate is the ratio of the internal concentrate loop flow rate to the total concentrate flow rate.
- To obtain higher recovery rates, flow rate through booster pump should be reduced as much as possible, taking into account that for safe operation, the flow rate must be at least 200 L/h.

Many preliminary experiments were carried out under various operating conditions (feed pressure, and brine recirculation rate) before carrying out the desalting experiments. The operation of the pilot unit is automated in order to ensure safe operation of the pumps (protection against dry run). The unit were operated under the following experimental program:

4.3.3.1 Pure Water Experiments

1- Seven experimental runs were carried out using one element NF90 membrane at pressures of 5, 10, 15, 20, 25, 30 and 37 bars. Maximum Operating Pressure of NF90 membrane is 41 bar (FILMTEC™ Membranes).

2- Six experimental runs were carried out using one element RO brackish water membrane at pressures of 5, 10, 15, 20, 25, and 30 bars. (Maximum Operating Pressure of RO brackish water membrane is 41 bar (**Toray**™ Membranes).

3- Seven experimental runs were carried out using one element RO Seawater membrane at pressures of 10, 20, 30, 37, 44, 51 and 60 bars. Maximum Operating Pressure of RO Seawater membrane is 69 bar (FILMTEC™ Membranes).

4.3.3.2 NaCl Solution Experiments

1- Ten experimental runs were carried out using one element NF90 membrane with NaCl solution of 2000, 7109 and 32556 mg/l concentrations at pressures of 5, 10, 15, 20, 25, 30 and 37 bars.

2- Six experimental runs were carried out using one element RO brackish water membrane with NaCl Solution of 7109 mg/l concentrations at pressures of 5, 10, 15, 20, 25, and 30 bars.

3- Four experimental runs were carried out using one element RO Seawater membrane with NaCl solution of 32556 mg/l concentration at pressures of 37, 44, 51 and 60 bars.

4.3.3.3 Seawater Experiments:

I- With Brine Recirculation

Twenty experimental runs were carried out using one element NF90 membrane at pressures of 10, 20, 30 and 37 bar, with brine recirculation ratio of 20 %, 40 %, 60 %, 80 % and 90 % for each operating pressure.

II- Without Brine Recirculation

1- Twenty four experimental runs were carried out using six elements NF90 membrane in series. The brine of the first desalination run was collected in a separate tank and re-entered to the system as a feed water. This step was repeated for a total of six times at a pressure of 10, 20, 30 and 37 bars individually. The permeate water obtained at a pressure of 37 bar was considered as a first pass desalination for the following second pass desalination.

2- Six experimental runs were carried out using one NF90 membrane and permeate produced from previous step (first pass desalination) at pressures of 6, 10, 15, 20, 25 and 30 bars. The obtained permeate is considered as a second pass desalination.

3- Six experimental runs were carried out using RO Brackish water membrane and the same permeate produced from the first pass desalination at pressures of 6, 10, 15, 20, 25 and 30 bars. The obtained permeate is also considered as a second pass desalination.

4- Four experimental runs were carried out using one element RO Seawater membrane at pressures of 37, 44, 51 and 60 bars.

5- Six experimental runs were carried out using six elements RO seawater membrane in series. The brine of the first desalination run was collected in a separate tank and re-entered to the system as a feed water. This step was repeated for a total of six times at a pressure of 60 bar. The permeate water obtained was considered as a first pass desalination for the following second pass desalination.

6- Four experimental runs were carried out using NF90 membrane and permeate produced from previous step (first pass desalination) at pressures of 5, 10, 15 and 20 bars. The obtained permeate is considered as a second pass desalination.

7- Four experimental runs were carried out using RO Brackish water membrane and the same permeate produced from the first pass desalination at pressures of 5, 10, 15 and 20 bars. The obtained permeate is also considered as a second pass desalination.

For each experiment the characteristics of permeate water was measured in terms of fluxes rate, recovery rate and rejection rate under different operating pressures.

CHAPTER FIVE: RESULTS AND DISCUSSION

5.1 General

This chapter will discuss the characteristics of the desalinated water that produced from using variable combination of NF and RO membranes. The characteristics of flux rate, hydraulic permeability, recovery and salt rejection will also be investigated.

5.2 First Package of Experiments

In this package of experiments, the unit was operated using NF90-2540, BW-2540 and SW30-2540 membranes with pure water. Each membrane was subjected to different operation pressures and the behavior of permeate water was measured in term of flux and hydraulic permeability. The process was repeated using different concentrations of NaCl solution in the same procedure. And also the behavior of permeate water was measured in terms of flux and hydraulic permeability. Details of flux and hydraulic permeability of pure water and NaCl solution are listed below:

5.2.1 Pure Water: Flux and Hydraulic Permeability

Using pure water, the permeability of each membrane was measured under different operation pressures (5 to 60 bar). The obtained permeate flux values for each examined membrane and their dependence on the pressure variations are presented in figure (5-1). The relationship between the fluxes and the operating pressures is linear with high correlation values. This linear behavior is described by a slope which corresponds to pure water permeability. From figure (5-1) it is clear that increasing of pressure leads to increase the flux. The SW30-2540 membrane has the lowest slope value (hydraulic permeability is 1.4484 $L.h^{-1}.m^{-2}.bar^{-1}$) and that was expected because this membrane has the narrowest skin's pores comparing to other membranes. NF90 membrane has the steepest slope value (hydraulic permeability is 5.5905 $L.h^{-1}.m^{-2}.bar^{-1}$) due to its' widest pores. This can be explained by considering transport through NF membranes as a result of two mass transfer mechanisms: convection and diffusion (Pontié et al 1997). Accordingly, the NF90 membrane is more affected by the applied pressure than the other two membranes.

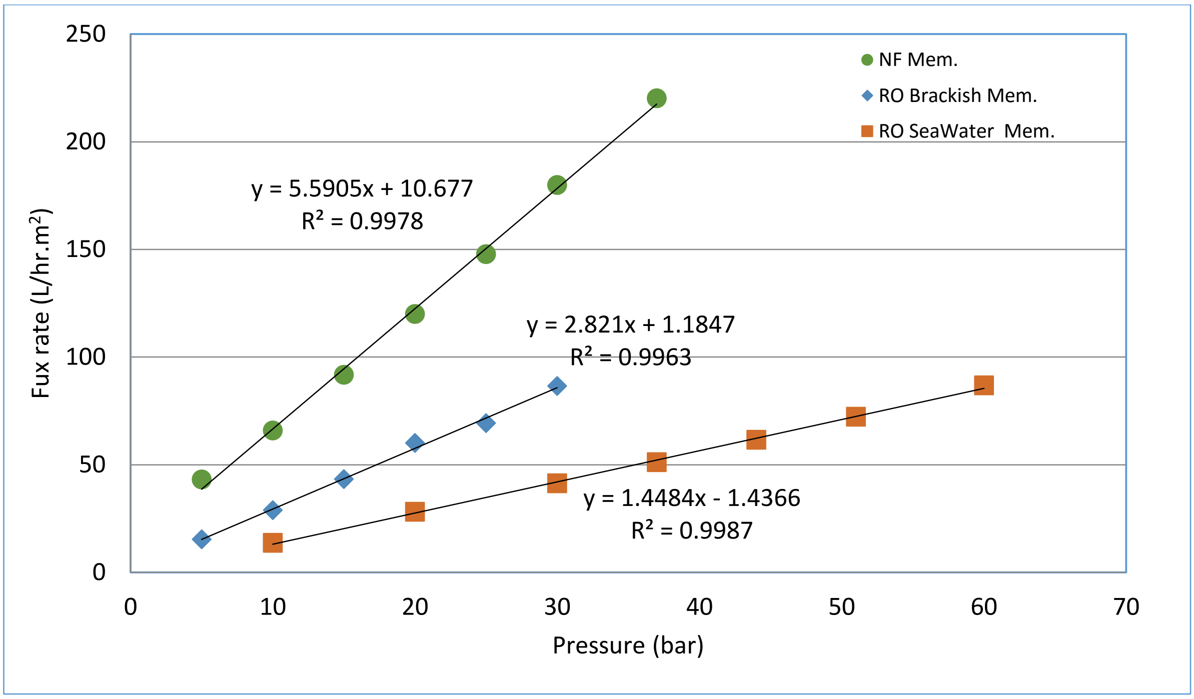


Figure (5-1): Relationships between pure water flux and pressure for the NF90-2540, BW-2540 and SW30-2540 membranes

5.2.2 NaCl Solutions

5.2.2.1 NF90-2540 with NaCl Solution (2000 mg/l)

A run using NaCl solution of (2000 mg/l) concentration was carried out and the obtained results were compared with the manufacture sheet of NF90 membrane. In this run different pressures (5 to 25) bar were applied and the flux rate of the solution was measured at each pressure value. Figure (5-2) illustrates the relationship between the flux rate and the pressure for the NaCl solution.

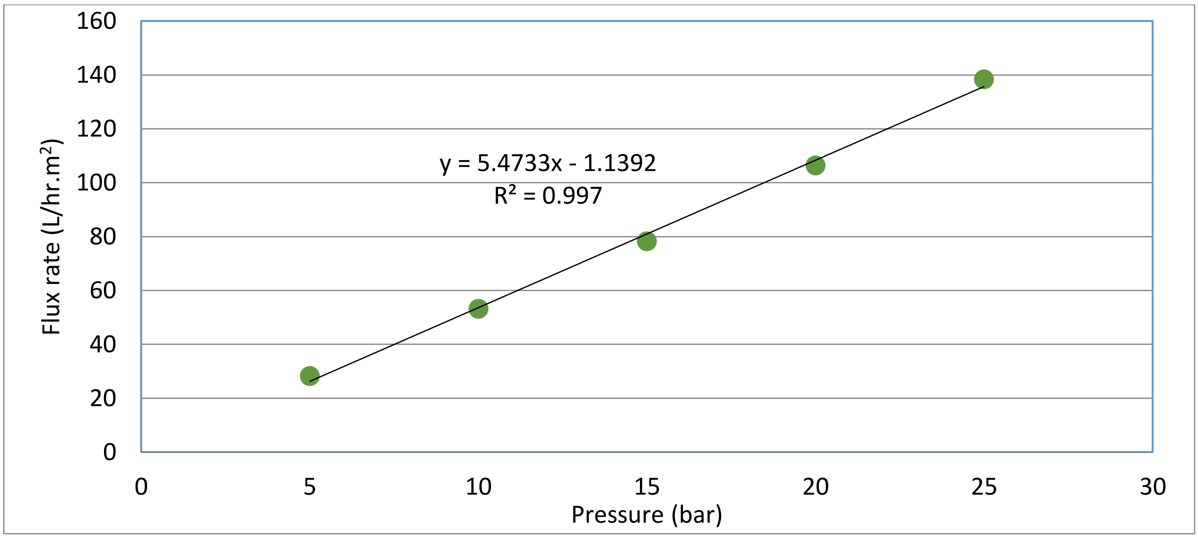


Figure (5-2): Effect of pressure on the permeate flux of 2000 mg/l NaCl solution for NF90 membrane

It was clear from figure (5-2), that there is a linear relationship between the flux and the pressure with correlation coefficient ($R^2 = 0.9968$). It is noted that the hydraulic permeability of NaCl solution (5.4733 $L.h^{-1}.m^{-2}.bar^{-1}$) is less than that of the pure water (5.5905 $L.h^{-1}.m^{-2}.bar^{-1}$); and also the flux of NaCl solution is less than flux in pure water. For example, at pressure 15 bar; the flux of NaCl solution (78.32L\hr.m^2) is less than the flux of pure water (91.70 L\hr.m^2). This reduction in flux crossing is increased when the ions are added. When compared with manufacture sheet, the value of the flux obtained from this experiment is closed to the ideal results illustrated in the manufacture sheet. As illustrated in the manufacture sheet, the flux at 5 bar should be (31.84 L/h.m^2), which is close to the experiment result (28.26 l/h.m^2).

5.2.2.2 NF 90-2540 (32556 mg/l NaCl)

A run using NaCl solution of (32556 mg/l) concentration was carried out on NF90 membrane to compare results with the results of another run using real seawater that has a concentration of (36580 mg/l). The applied pressure in the two runs was the same that it was varied from 10 to 37 bar. The flux rate of the solution was measured at each pressure value. Figure (5-3) shows a linear relationship of flux rate with pressure for NaCl solution and seawater. It is noted that the flux and hydraulic permeability in seawater are less than these of the aqueous solution. For example, at pressure of 37 bar the flux of the seawater was (27.73 L\hr.m^2) and the flux of solute was (34.33 L\hr.m^2), and that may occur probably due to the presence of other contaminates in the real seawater such as Magnesium with concentration of (1451 mg\l) that increase the osmotic pressure. It is also noted that the hydraulic permeability of the seawater (0.9683 $L.h^{-1}.m^{-2}.bar^{-1}$) is less than that of the NaCl solution (1.1513 $L.h^{-1}.m^{-2}.bar^{-1}$).

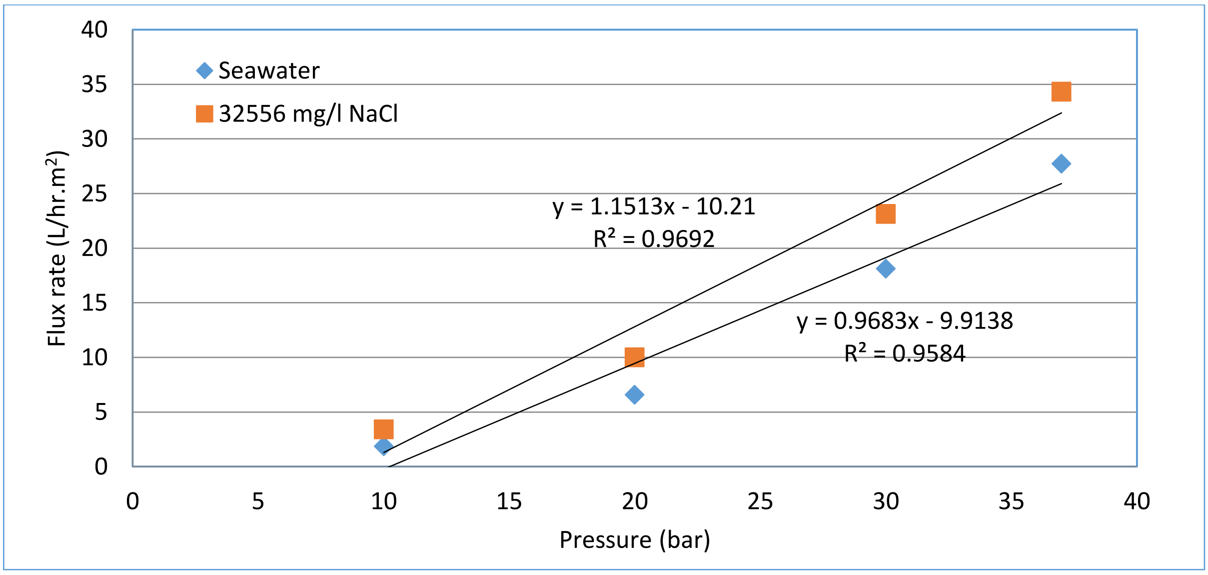


Figure (5-3): Effect of pressure on the permeate flux of (33560 mg/l) NaCl solution and seawater for NF90

5.3 Second Package of Experiments

In this package of experiment, one element NF90 membrane was fed with seawater. The desalination process were carried out at different pressure values 10, 20, 30 and 37 bar. During the experiment, a part of the brine was recirculated to the membrane. At each pressure value 0.20, 0.40, 0.60, 0.80 and 0.90 of the brine were was recirculated to the membrane see figure (4-6). For each run, the fluxes, recovery rejection rate and remaining ions under different operating pressures of permeate water were measured as described below.

5.3.1 Flux

Figure (5.4) shows the relationship between the flux rate and the recirculation ratio at deferent operating pressures. It is clear that at pressures 10 and 20 bars recirculation does not affect the flux rate, because both of the pressure and the rejection rate are low. At these conditions, the TDS concentration of the brine is almost the same as that of feed water; so, the recirculation of the brine has no significant effect. In the other hand at higher pressure values such as 30 and 37 bar, brine recirculation affects the flux rate because increasing pressure lead to increase rejection rate, the thing which, increases brine concentration too. With recirculation, the TDS concentration of water feeding the membrane increases, and that decreases flux rate through membrane. It is observed that at pressure value 37 bar and brine recirculation ratio (20.10 %) the resulted TDS concentration of membrane feed water is (37148.32 mg\L) and the flux rate is (26.54 L/hr.m^2). While at the same pressure value (37 bar) and higher recirculation ratio (89.50 %) the TDS of the membrane feed water increases to (47970.69 mg\L), while the flux decreases to (15.20 L/hr.m^2).

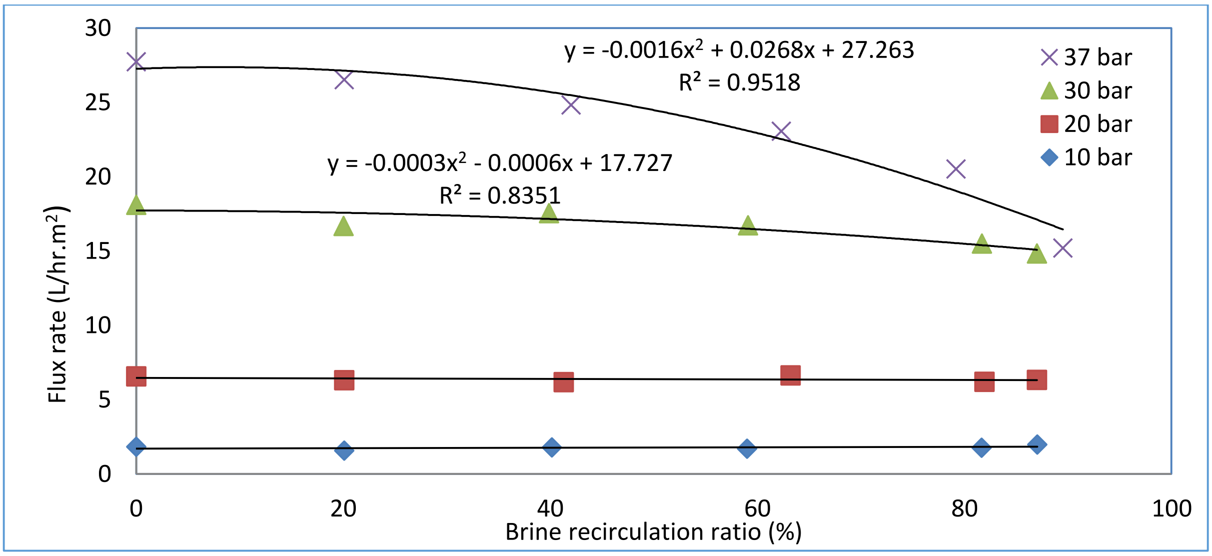


Figure (5-4): Effect of brine recirculation ratio on the permeate flux of seawater for NF90 at deferent pressures

5.3.2 Recovery Rate

The recovery rate is the ratio of the permeate flowrate to the flowrate from raw seawater feed tank. Figure (5-5) shows the relationship between the recovery rate and the brine recirculation ratio for one element. It is noted that, the recovery rate increases with increases of the recirculation ratio. It is observed too, that at 37 bar and recirculation ratio (89.50%) the recovery rate (33.06%) which is higher than the value of the recovery rate (7.79%), without recirculation. This increase in recovery rate occurs due to the (89.50%) substitution of the raw seawater deeding the membrane with brine water. It is important to note that, high percentage of brine recirculation leads to membrane clogging.

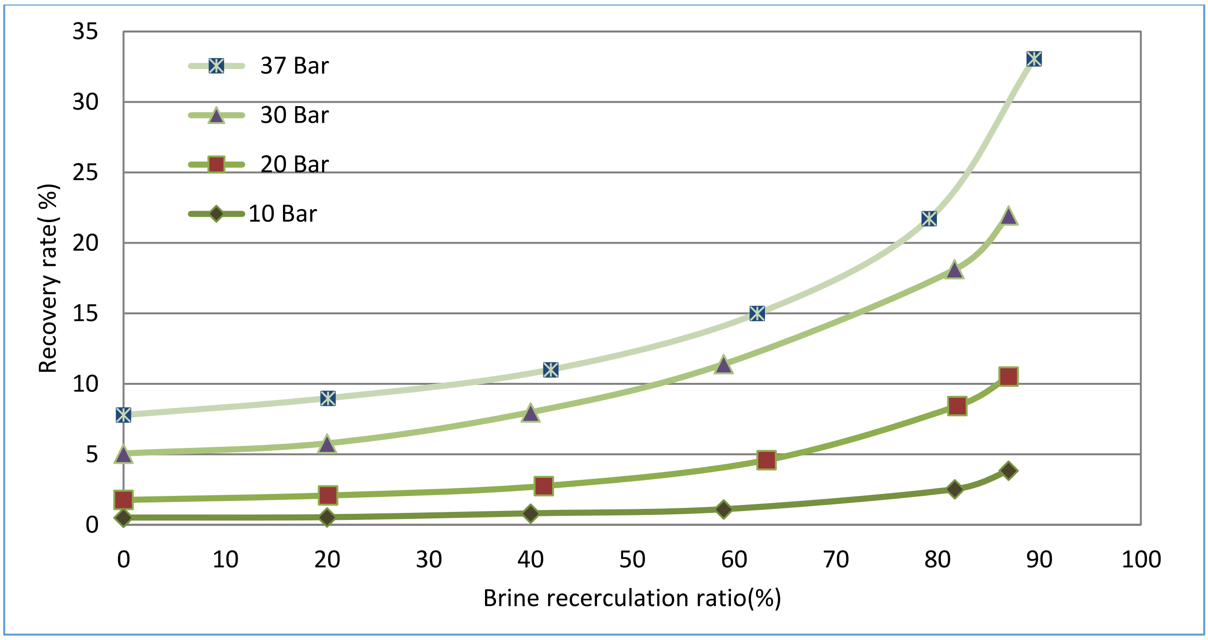


Figure (5-5): Effect of brine recirculation ratio on recovery rate of seawater desalination for NF90 at deferent pressures

5.3.3 Rejection Rate

5.3.3.1 TDS

Figure (5-6) shows the relationship between the TDS rejection rate and brine recirculation ratio. This figure illustrates that the TDS rejection rate almost does not change at pressure values 10 or 20 bar, and that occurs due to little change of concentration of water that feed the membrane. At pressures value of 30 and 37 bars rejection rate decreases with the increases of brine recirculation ratio which takes place due to pressure increase which leads to increase in membrane rejection and increase in concentration of the brine. These conditions finally, lead to decrease in rejection rate of the system as all. It is observed that at 37 bar with (89.50%) recirculation ratio, the feed concentration of membrane is (47970.69 mg\l). Rejection of membrane it self is (80.25 %), and rejection of the system due to concentration of sea water

(36580mg\l) is (74.10%) which it is smaller than the value of the rejection rate (83.83%) at 37 bar without recirculation for membrane and the system over all. This increase in recovery rate occurs due to the (89.50%) substitution of the raw seawater feeding the membrane with brine water.

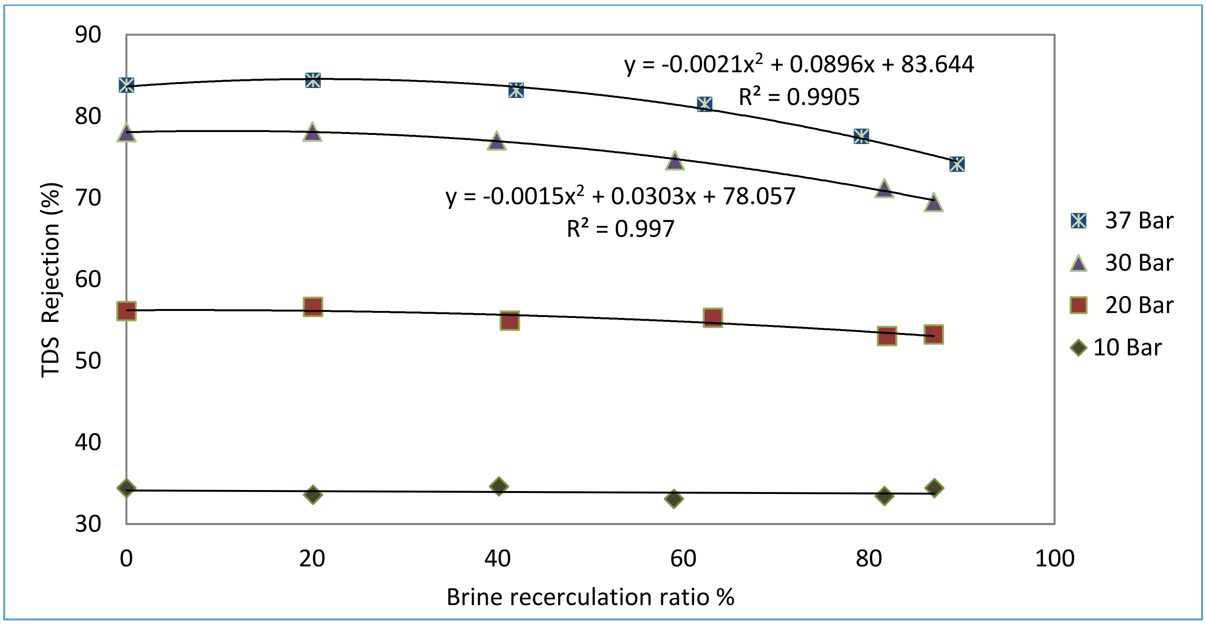


Figure (5-6): Effect of brine recirculation ratio on TDS rejection rate in seawater desalination for NF90 at deferent pressures

5.3.3.2 Chloride

Figure (5-7) shows the relationship between chloride rejection rate and brine recirculation ratio. Because chloride is the main component of the TDS of the seawater, the behavior of chloride is very similar to that of TDS.

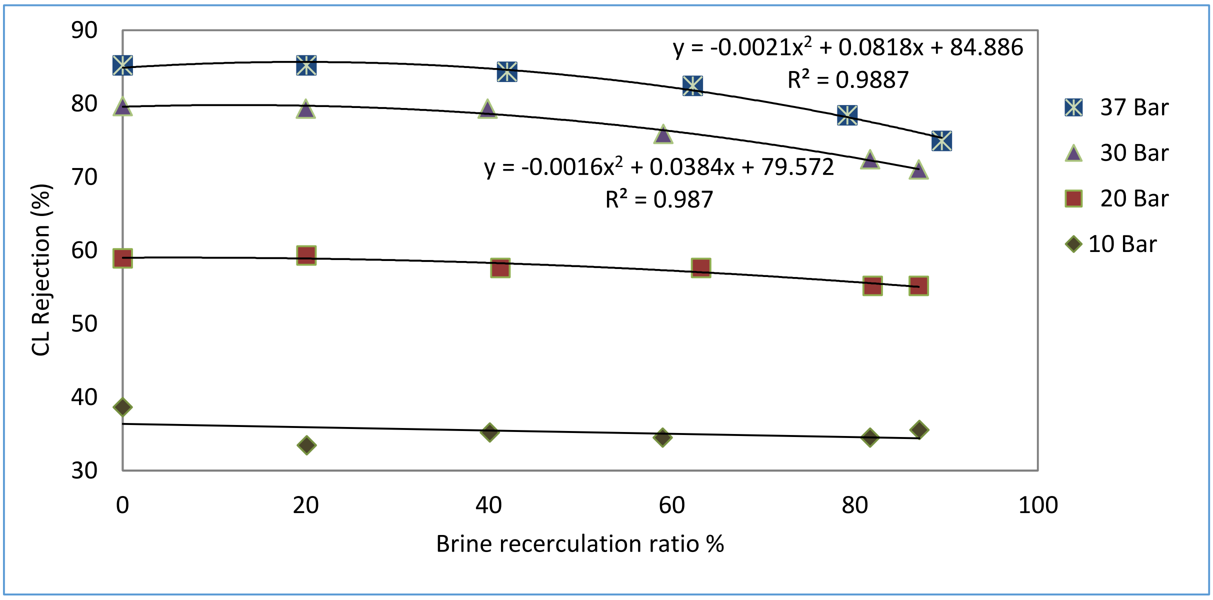


Figure (5-7): Effect of brine recirculation ratio on chloride rejection rate in seawater desalination for NF90 at deferent pressures

The relationship between the rejection ratio and brine recirculation ratio for other elements listed in table (4-3) are illustrated in appendix (1)

5.3.4 Remaining Ions

5.3.4.1 TDS

Figure (5-8) shows the relationship between the TDS removal and the brine recirculation ratio using one NF90 membrane element. TDS concentration almost does not change with the pressure values of 10 and 20 bars and that occurs due to the little change in feed concentrations. At pressures value of 30 and 37 bars TDS concentration increases with the increases of brine recirculation ratio which takes place due to pressure increase which leads to increase in membrane rejection and increase in concentration of the brine. These conditions finally, lead to increase the TDS concentration of the system as all. It is observed that at 37 bar with (89.50%) recirculation ratio, the permeate TDS concentration is (9477 mg\l) and it is higher than the permeate TDS concentration at 37 bar without recirculation which is (5915 mg\l). This increase in TDS value occurs due to the (89.50%) substitution of the raw seawater feeding the membrane with brine water.

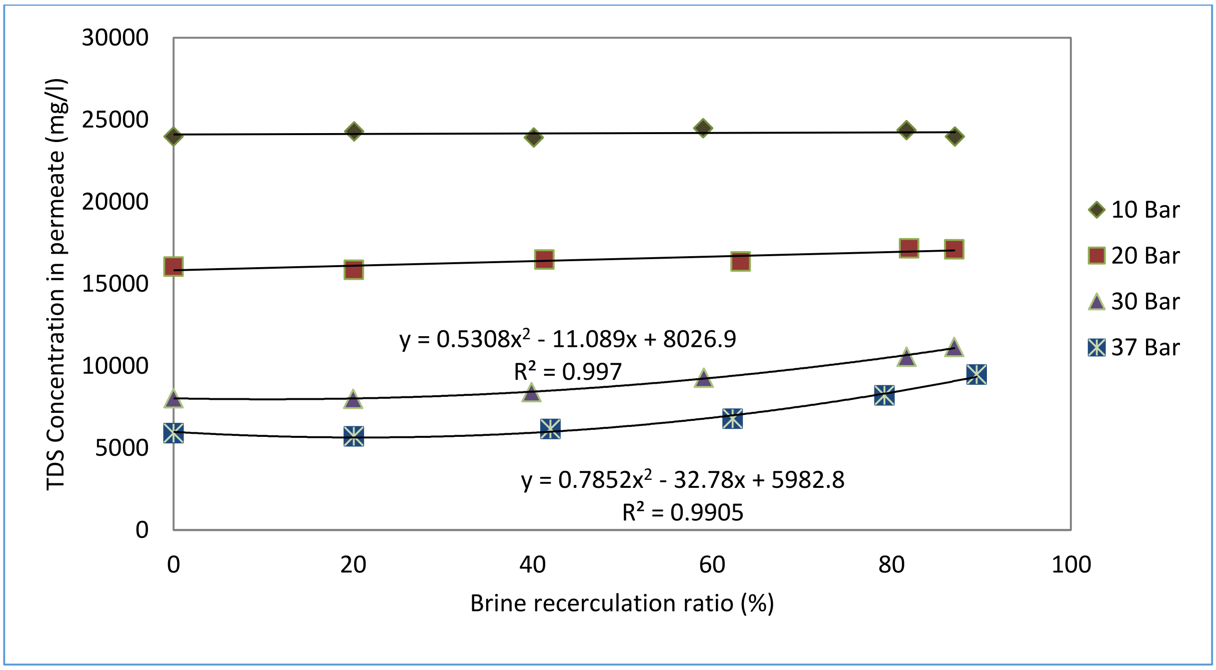


Figure (5-8): Effect of brine recirculation ratio on TDS removal in seawater desalination for NF90 at deferent pressures

5.3.4.2 Chloride

Figure (5-9) shows the relationship between the chloride removal and brine recirculation ratio. The chloride concentration almost does not change with the pressure values of 10 and 20 bars and that occurs due to the little change in feed concentrations. At pressures value of 30 and 37 bars chloride concentration increases with the increases of brine recirculation ratio which takes place due to pressure increase which leads to increase in membrane rejection and increase in concentration of the brine. These conditions finally, lead to increase the chloride concentration of the system as all. While at pressures value of 30 and 37 bars the chloride concentration in the permeate increases with the increases of brine recirculation ratio which takes place due to pressure increase which leads to increase in membrane rejection and increase in concentration of the brine. These conditions finally, lead to increase the chloride concentration in the permeate of the system as all. It is also noted that at 37 bar with (89.50%) brine recirculation ratio, the chloride concentration in permeate is (5216 mg\l) and it is higher than the chloride concentration in the permeate at 37 bar without recirculation which is (3079 mg\l). This increase occurs due to the (89.50%) substitution of the raw seawater feeding the membrane with brine water.

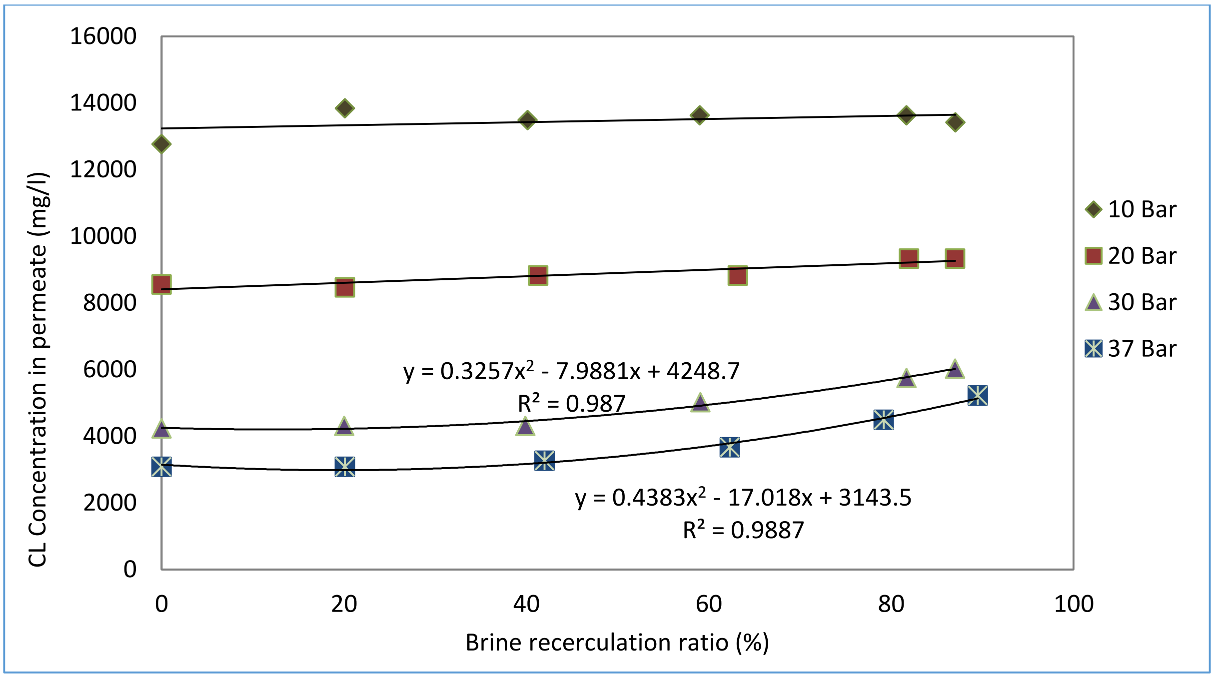


Figure (5-9): Effect of brine recirculation ratio on chloride removal in seawater desalination for NF90 at deferent pressures

The relationship between the ions removal and brine recirculation ratio for other elements listed in table (4-3) are illustrated in appendix (1).

5.3.5 Specific Energy Consumption (SEC)

The relationship between the SEC for one cubic meter of permeate and brine recirculation ratio using one element of NF90 membrane is illustrated in figure (5-10). It is noted that the SEC value decrease with the increasing brine recirculation ratio at all applied pressure values (10, 20, 30, 37 bars); because the increase in brine recirculation ratio increases the recovery rate, and consequently decreases the SEC. It is also noted that from the figure (5.10) at 37 bar pressure value and (89.5 %) brine recirculation ratio the value of SEC is (4.09 kWh/m^3) which is less than the value of SEC without brine recirculation which is (17.35 kWh/m^3). That occurs because when the brine recirculation ratio increases, the recovery rate increases, and according to the equation (4.7) the SEC value decreases.

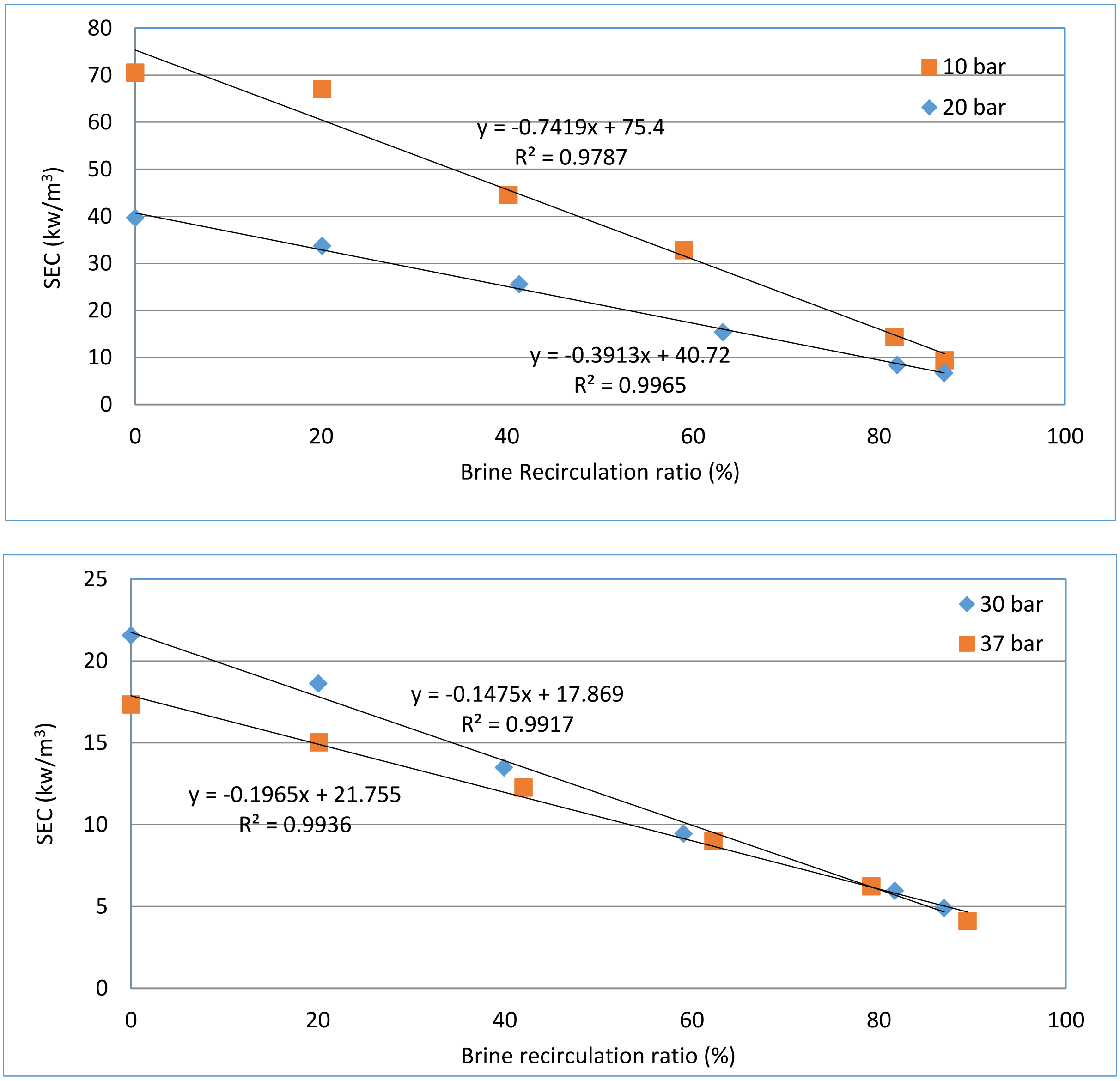


Figure (5-10): Relationship between SEC and brine recirculation ratio for NF90 at deferent pressures in seawater desalination

5.4 Third Package of Experiments

In this package, the unit was operated to desalinate sweater using six elements of NF90 membrane in series (as used in real seawater desalination planets) *without internal recirculation of the brine*. The brine of the first desalination run was collected in a separate tank and re-entered to the system as a feed water. This step was repeated for six times at a pressure of 10, 20, 30 and 37 bars individually. The permeate water obtained at a pressure of 37 bar was considered as a first pass desalination for the following second pass desalination. For each run; experimental data for the permeate flux, recovery rate, rejection rate and the ions concentration were obtained. In addition, for each run the concentration of the feed water of each one of the six membranes was calculated at 10, 20, 30 and 37 bar.

5.4.1 Flux

Figure (5-11) shows the relationship between the flux rate and the operating pressures. It is clear that, the flux rate increases linearly with the increase in pressure value as in the case of the NaCl solution observed previously. The value of the flux rate at 37 bar in the first membrane is (27.73 L/hr.m^2) which is higher than the value of the flux rate for the same membrane at 10 bar (1.85 L/hr.m^2). That occurs due to the increase of pressure. It is also observed that, the value of the flux rate in first membrane > the second membrane > third membrane> forth membrane> fifth membrane> sixth membrane. That takes place because the TDS concentration of the feed water is increased. At 37 bar the feed concentration of the first membrane is (36,580 mg/l), and the feed concentration of the sixth membrane is (48,991.1mg/l), accordingly, it is concluded that, the TDS concentration of the feed water significantly affect the flux rate.

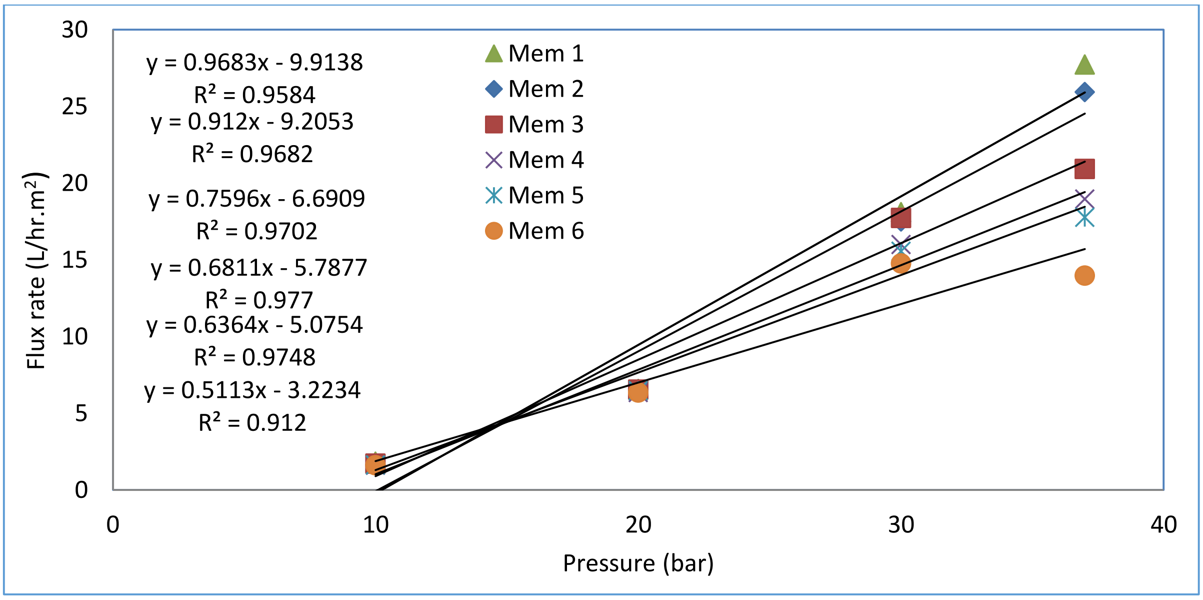


Figure (5-11): Relationship between permeate flux and operating pressures using six NF90 elements in series in seawater desalination

5.4.2 Hydraulic Permeability (Lp)

The values of the Lp of the six membranes are shown in figure (5-11) as the slopes of the flux-pressure relationships. Figure (5-12) shows the values of the Lp for each membrane in the system. It clearly noted that Lp values linearly decrease from the first membrane which is (0.9683 $L.h^{-1}.m^{-2}.bar^{-1}$) to the sixth membranes which is (0.5113 $L.h-1.m^{-2}.bar^{-1}$). And that probably occurs due to the increase in the TDS concentration of the feed water and the decrease of pressure due to drop lose occurring through the membranes.

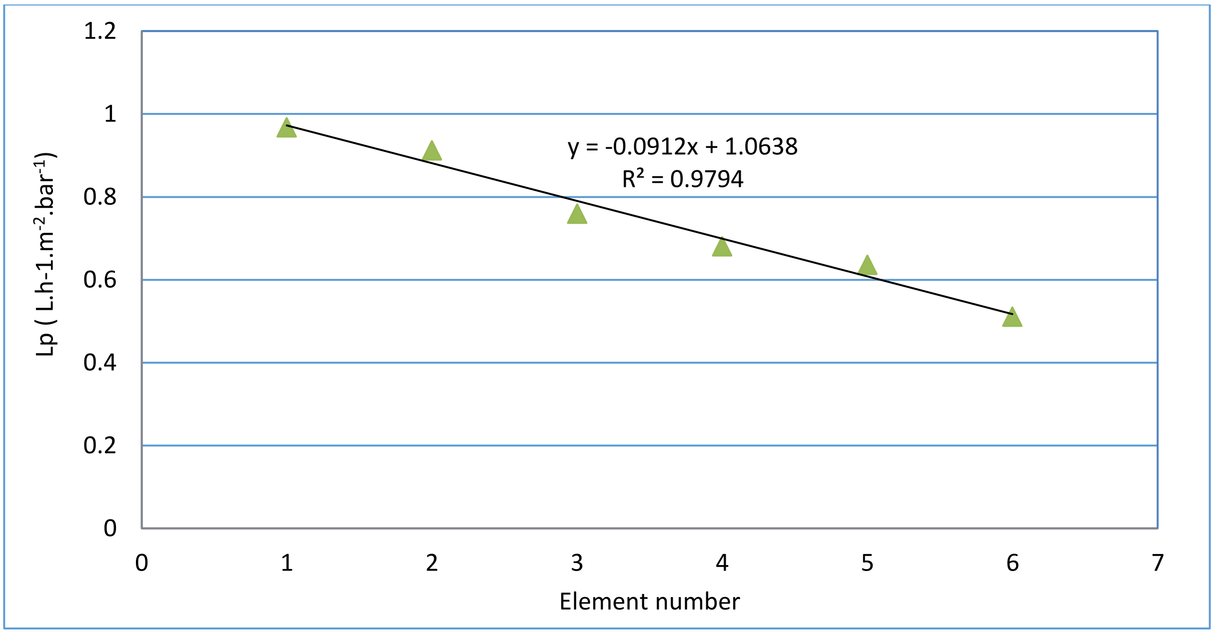


Figure (5-12): Hydraulic permeability values of six NF90 elements in series in seawater desalination

5.4.3 Recovery Rate

Figure (5-13) shows the relationship between the cumulative recovery rate of the six NF90 membranes in series and the operating pressures. It is noted that, the cumulative recovery rate increases with the increase of the pressure. It is also observed that, at pressure value 37 bar, the value of the cumulative recovery rate is (34.75%), which is higher than the value of the recovery rate at 10 bar, which is (2.76%). That occurs because the increase of pressure. The value of the recovery rate of the first membrane is higher than the value of the second membrane and that of third and so on. The reduction in the recovery rate value occurs because the TDS concentration of feed water in the first membrane is lower than the TDS concentration in the second one and so on, and also because of the decrease of pressure due to drop lose through membranes.

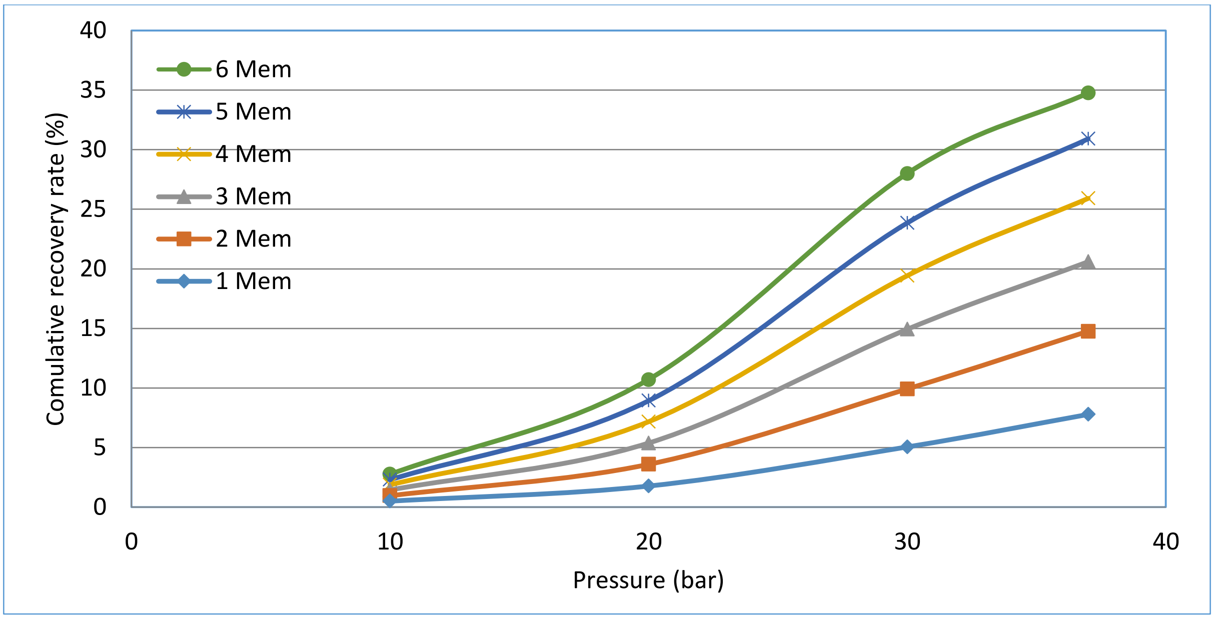


Figure (5-13): Relationship between the cumulative recovery rate in seawater desalination using six NF90 elements in series and the operating pressure

4.4.4 Recovery Rate With / Without Brine Recirculation

Figure (5.14a) and figure (5-14b) illustrate the relationship between the cumulative recovery rate and the number of NF90 elements used, as well as the relationship between the recovery rate and brine recirculation ratio respectively at constant applied pressure value (37 bar). It is observed that when the five elements were used, the cumulative recovery rate value is (30.91%). This value is equivalent to the value obtained when one element is used with (87 %) brine recirculation ratio. It is important to mention that when (87%) of the brine were recirculated; the value of the TDS concentration is (9074 mg/l), which is higher than the value obtained when fife elements in series were used (7611 mg/l), as illustrated in figure (5.15).

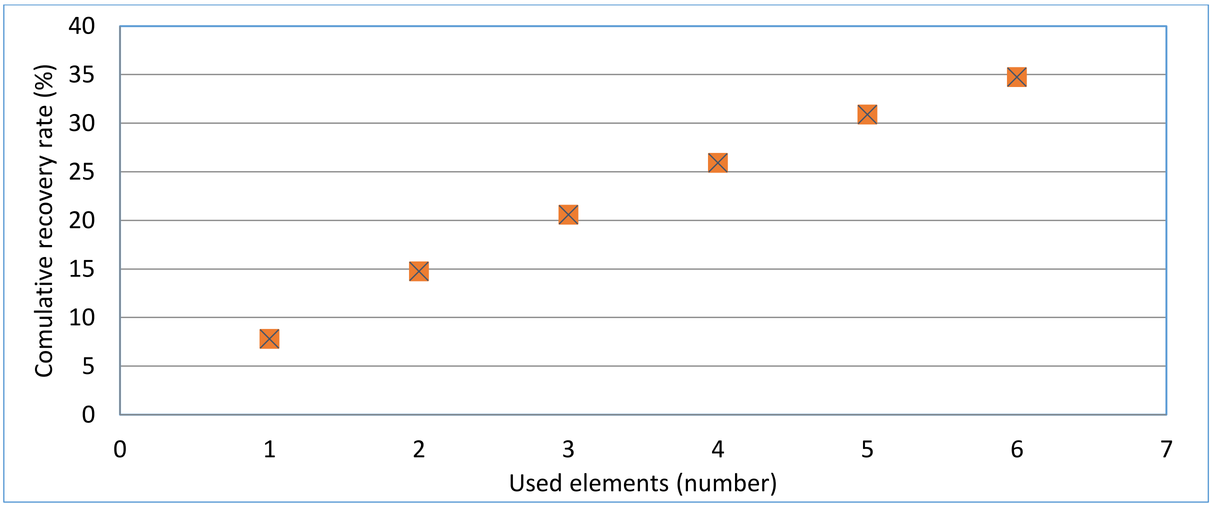


Figure (5-14a): Relationship between cumulative recovery rate and numbers of NF90 used elements (applied pressure is 37 bar)

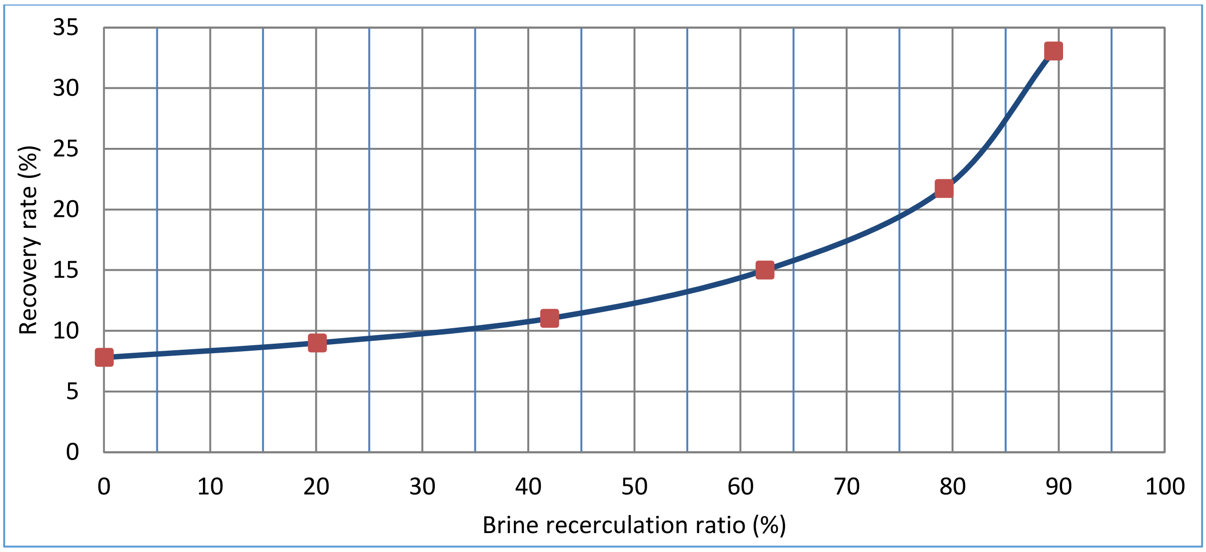


Figure (5-14b): Relationship between cumulative recovery rate in seawater desalination and brine recirculation ratio using one NF90 membrane (applied pressure is 37 bar)

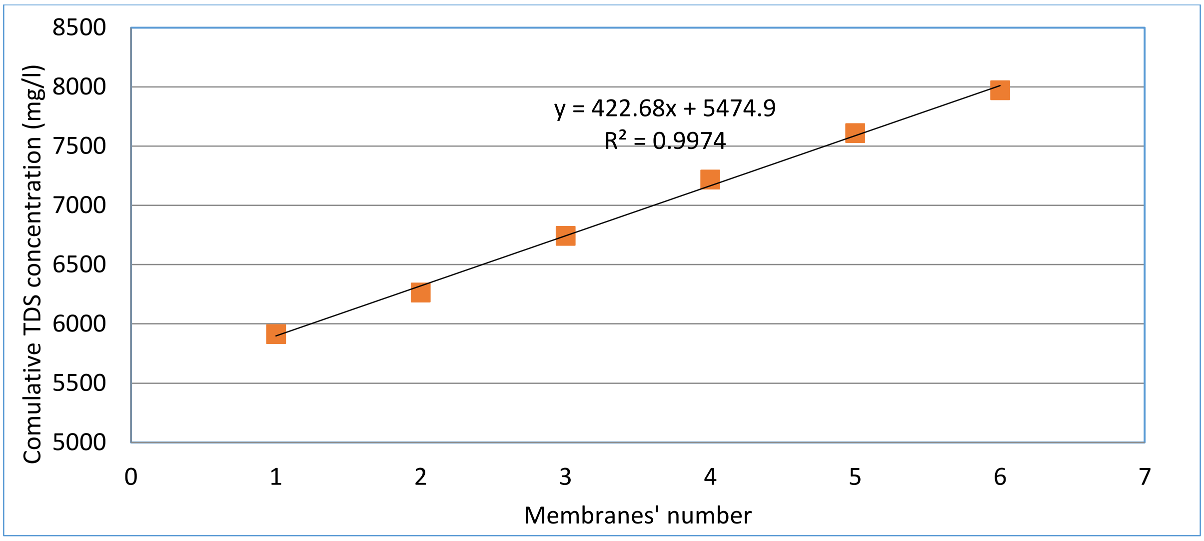


Figure (5-15): Relationship between TDS removal in seawater desalination and NF90 membranes' numbers (applied pressure is 37 bar)

5.4.5 Rejection Rate

5.4.5.1 TDS

The effect of the operating pressures on the TDS rejection rate is illustrated in figure (5-16). The results show that when the operating pressure increases, the rejection rate of the TDS increases. However, at pressure value of 37 bar the individual rejection rate of the first membrane is (83.83 %), which is higher than those of the second membrane to the sixth membrane (77.18 %). The reduction in the rejection rate value occurs because the TDS concentration of feed water in the first membrane is higher than the TDS concentration in the second one and so on and also because of the decrease of pressure due to drop lose through membranes.

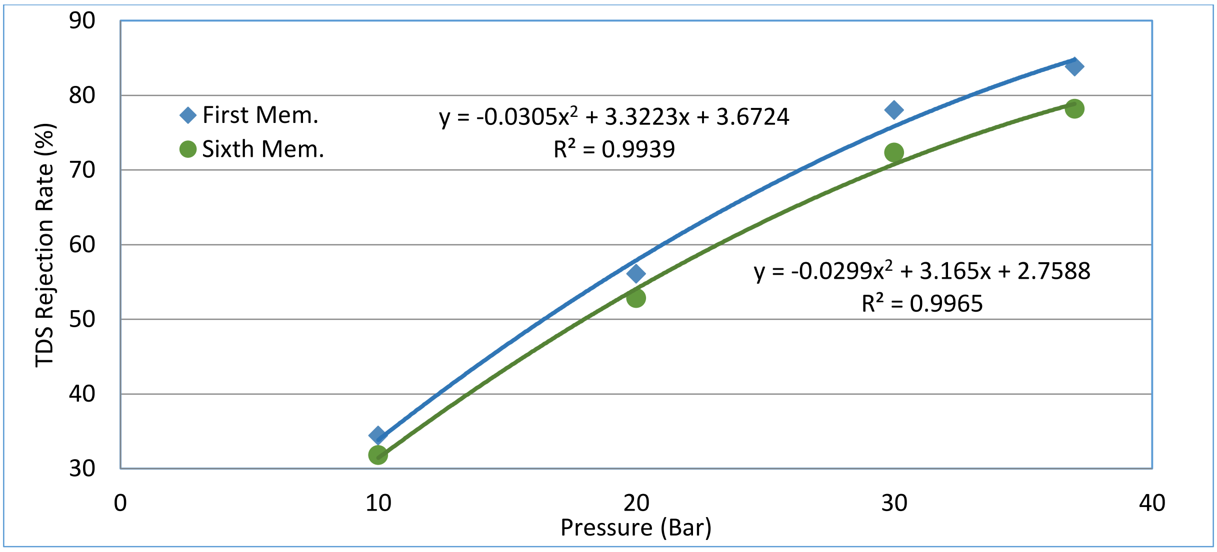


Figure (5-16): Effect of pressure on TDS rejection using six NF90 elements in series in seawater desalination

The pressure drop is not the main influencing factor. TDS concentration plays an important role. The cumulative rejection rate of the six elements in series increases with pressure. At pressure value of 37 bar the value of the cumulative rejection rate is (78.21%) and the value of the recovery rate is (34.75%).

5.4.5.2 Chloride

The effect of operating pressures on chloride rejection is shown in figure (5-17). When operating pressure increases, the removal of chloride increases. However, at pressure of 37 bar the individual rejection rate value of the first membrane is (85.20 %), which is higher than the values of the other fife membranes. The value of the rejection rate of the sixth membrane is (79.26 %) and that occurs due to reasons mentioned in 5.4.5.1.

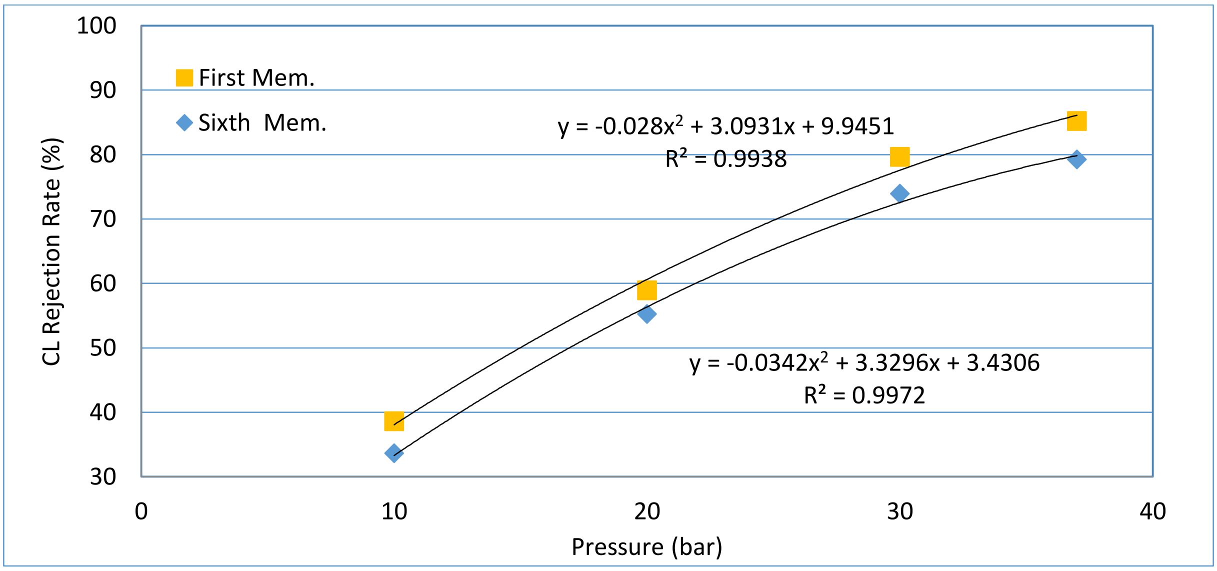


Figure (5-17): Effect of pressure on chloride rejection using six NF90 elements in series in seawater desalination

The relationship between the rejection rate of the ions and the applied pressure for other elements listed in table (4-3) are illustrated in appendix (2).

5.4.6 Remaining Ions

5.4.6.1 TDS

The effect of operating pressures on TDS removal is shown in figure (5-18). The results show that when the operating pressure increases the TDS concentration decreases. However, at pressure of 37 bar the individual value of the TDS concentration of the first membrane is (5915 mg\l) which is less than the value of second one and so on, where the value of the sixth membrane is (10848 mg\l), and that occurs due to the reasons mentioned in 5.4.5.1. The cumulative TDS concentration of the six NF90 elements in series at 37 bar pressure is (7971 mg\l), while the values of the rejection rate is (78.21%) and the value of the recovery rate is (34.75%).

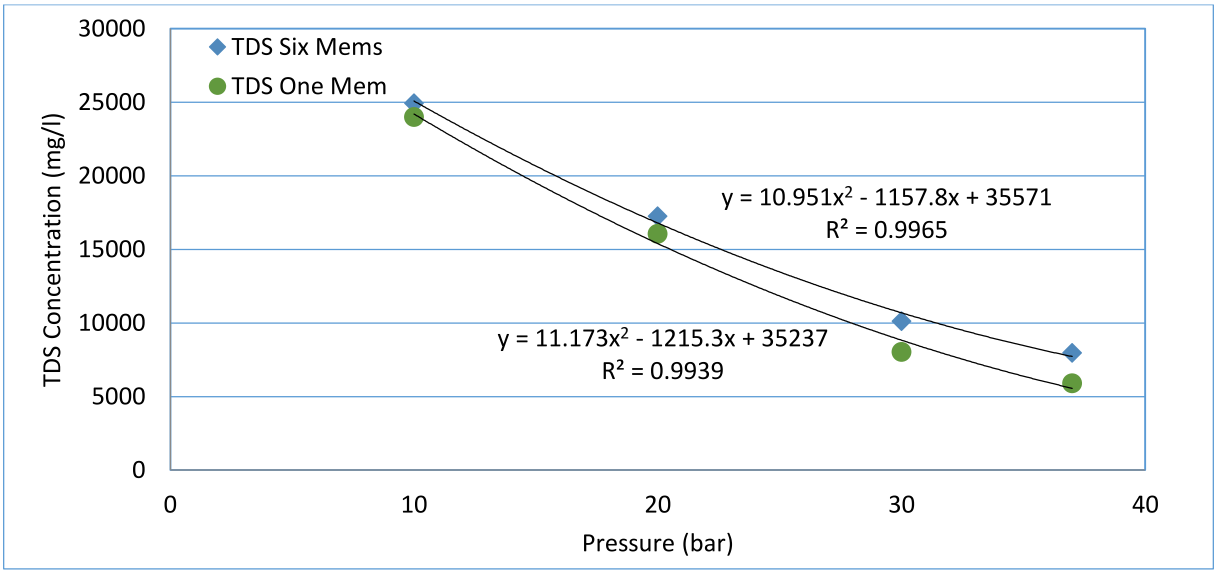


Figure (5-18): Effect of pressure on TDS removal using six NF90 elements in series in seawater desalination

5.4.6.2 Chloride

The effect of the operating pressure on chloride removal is shown in figure (5-19). The results show that when the operating pressure increases the chloride concentration value decreases. However, at pressure of 37 bar the value of the individual chloride concentration of the first membrane is (3079 mg\l). This value is lower than that of the second membrane < that of the third < that of the forth < that of the fifth < that of the sixth membrane (5977 mg\l). The increase in chloride concentration occurs due to the reasons mentioned in 5.4.5.1. The cumulative chloride concentration of the six NF90 elements in series at 37 bar pressure is (4314.17 mg\l), while the values of the rejection rate is (79.26%) and the value of the recovery rate is (34.75%).

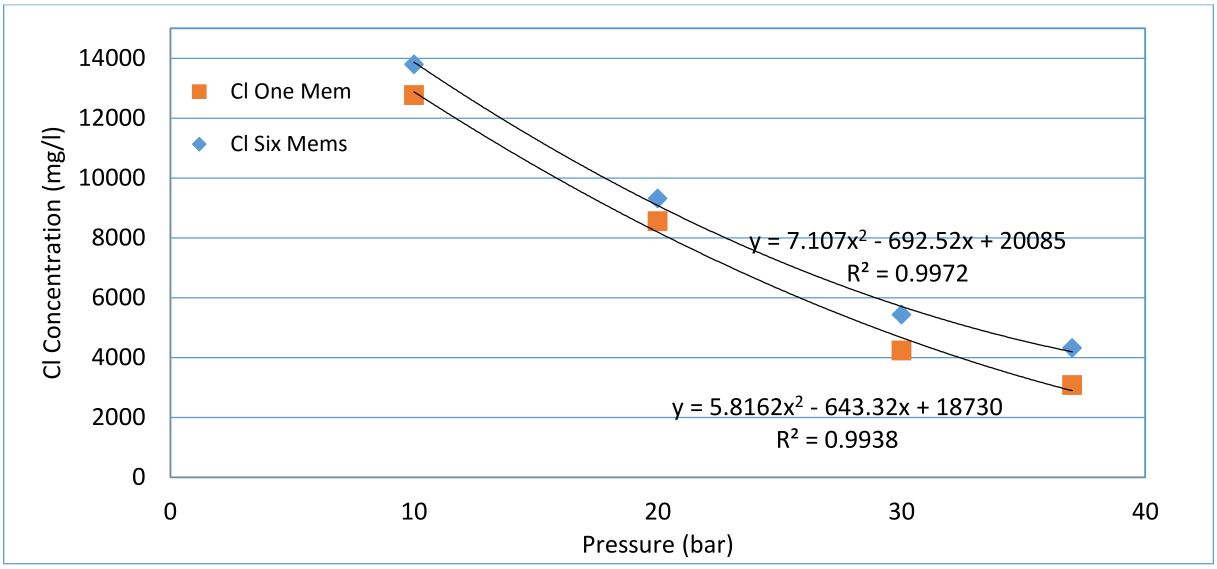


Figure (5-19): Effect of pressure on chloride removal in seawater desalination using six NF90 elements in series

The relationship between the ions removal and the operating pressure for the other elements listed in table (4-3) are illustrated in appendix (2).

5.4.7 Specific Energy Consumption (SEC)

The relationship between the SEC of one cubic meter of permeate and operating pressure for six NF90 elements in series is illustrated in figure (5-20). It shows that the SEC decreases with increasing pressure, and that because increasing pressure leads to increase of recovery rate which decrease SEC of the desalination. At 10 bar pressure, the recovery rate value is (2.76 %) and the SEC value is (12.37 kWh/m^3) while at pressure value 37 bar the value of the SEC decreases to (3.72 kWh/m^3) because the recovery rate increases to (34.75 %).

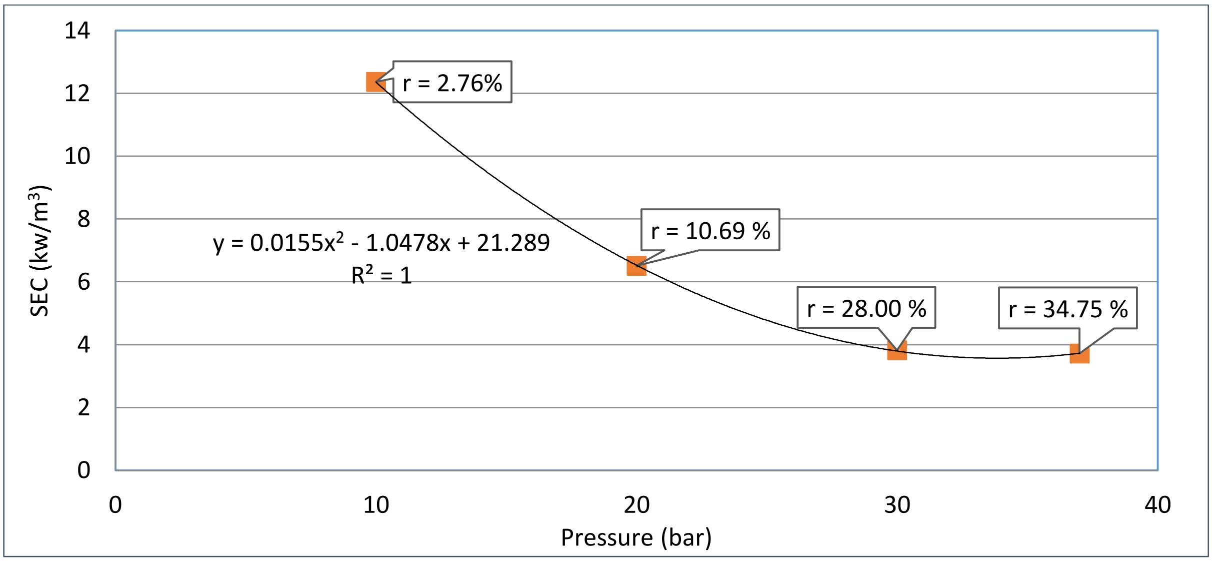


Figure (5-20): Relationship between energy consumption and pressure using six NF90 elements in series in seawater desalination

5.5 Fuorth Package of Experiments: Second Pass Desalination using NF90 Membrane

In the previous package of experiments the permeate of desalination process at 37 bar pressure using six NF90 membranes in series was collected in a separate tank and considered as a first pass of desalination process. The characteristics of permeate are listed in table (5-1).

Table (5-1): Permeate characteristics of first pass desalination using six NF90 elements in series (applied pressure is 37 bar)

Parameter	Unit	Mem. 1	Mem. 2	Mem. 3	Mem. 4	Mem. 5	Mem. 6	Weighted Average
E.C	Micro mho/cm	9540	10710	12860	14650	15610	17490	12857.32
TDS	mg/l	5915	6640	7973	9083	9678	10844	7971.54
Chloride	mg/l as CL	3079	3079	4311	4963	5361	5977	4314.17
Nitrate	mg/l as NO_3	2	2	3	4	3	4	2.83
Sulfate	mg/l as SO_4	12	14	18	22	24	30	18.64
Alkalinity	mg/l as CO_3	10	12	12	14	14	15	12.48
Hardness	ppm as $CaCO_3$	245	271	295	314	416	422	313.16
Calcium	ppm as Ca	22	22	22	27	30	32	25.01
Magnesium	ppm as Mg	46	52	58	60	83	83	60.74
Potassium	ppm as K	97	104	124	134	45	154	107.54
Sodium	ppm as Na	2000	2350	2700	3200	3500	4000	2806.71

In this package of experiments, the unit was operated using one NF90element and the permeate collected in the previous package (at 37 bae pressure) used as a feed for the second pass of desalination. The experiments were carried out at pressures of 5, 10, 15, 20, 25 and 30 bars. For each experiment, the characteristics of permeate water were measured in terms of flux, recovery rate and rejection rate under the operating pressure values mentioned above as flow:

5.5.1 NaCl Solution (7109 mg/l)

A run using NaCl solution of (7109 mg/l) concentration was carried out using NF90 membrane to compare the obtained results with the results obtained from the other runs in this package. The same applied pressure values used in the NaCl solution experiment are used in the real water (collected permeate) experiments. These values varied from 5 to 30 bar. In each run, the value of the flux rate of the solution was measured. Figure (5-21) shows the relationship between the flux rate and the pressure. It is noted that the flux rate increases linearly with the pressure.

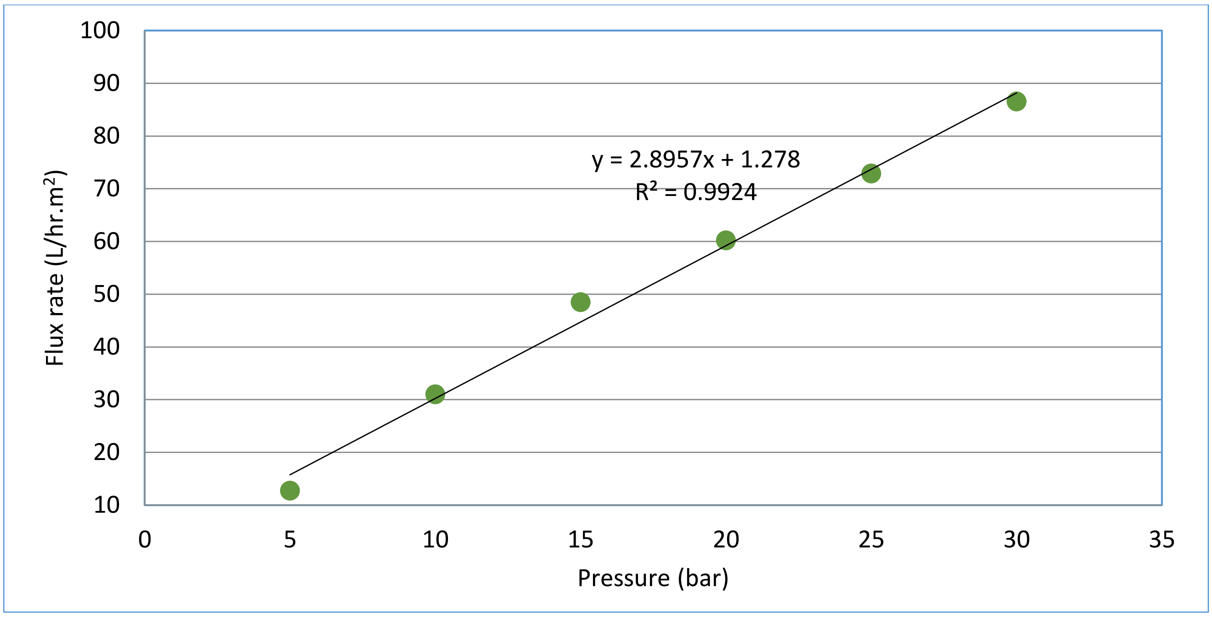


Figure (5-21): Relationship between the flux rate using (7109 mg/l) NaCl solution and the pressure for NF90 membrane

5.5.2 Real Water

5.5.2.1 Flux Rate and Hydraulic Permeability

Figure (5-22) shows the relationship between the flux rate and the pressure using NF90 membrane fed by both NaCl solution (7109 mg/l) and real water (TDS concentration 7971.54 mg/l). The flux rate increases linearly with the pressure. It is observed that the flux rate of the real water is less than flux rate of the NaCl solution at all pressure values. The (Lp) of real water in second pass desalination is (2.6676 L.h^{-1}.m^{-2}.bar^{-1}) and its less than (Lp) when NaCl solution is used (2.8957 L.h^{-1}.m^{-2}.bar^{-1}), and that due to the presence of other ions in the real water.

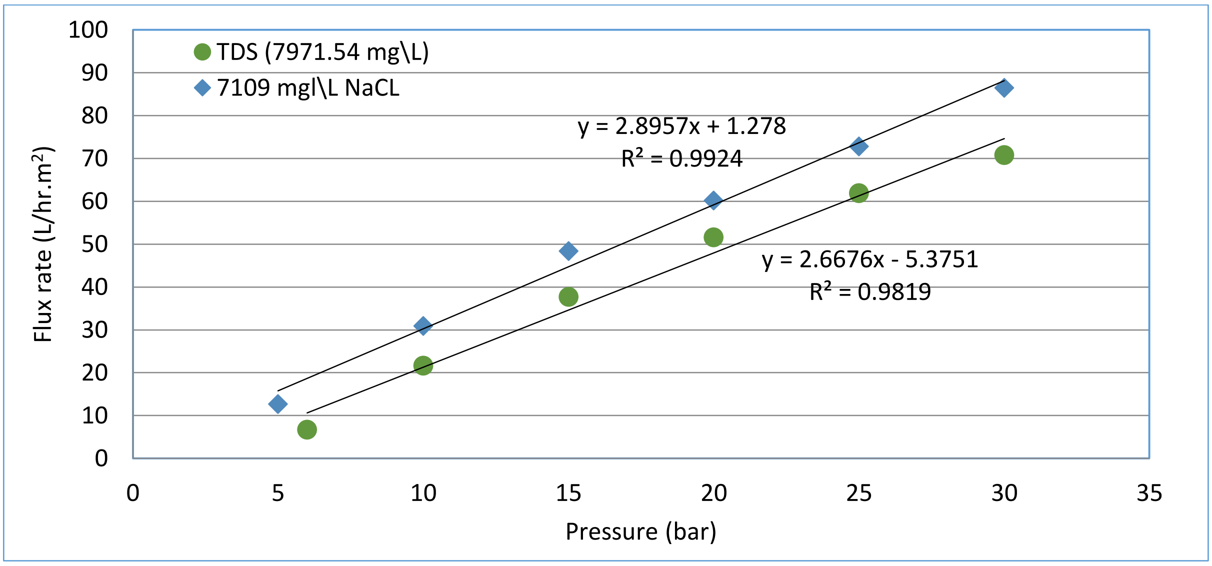


Figure (5-22): Relationship between the flux rate using real water or NaCl solution and the pressure for NF90 membrane

5.5.2.2 Recovery Rate

Figure (5-23) shows the relationship between the recovery rate and operating pressure for one NF90 elements. It is noted that, the recovery rate increase linearly with the pressure.

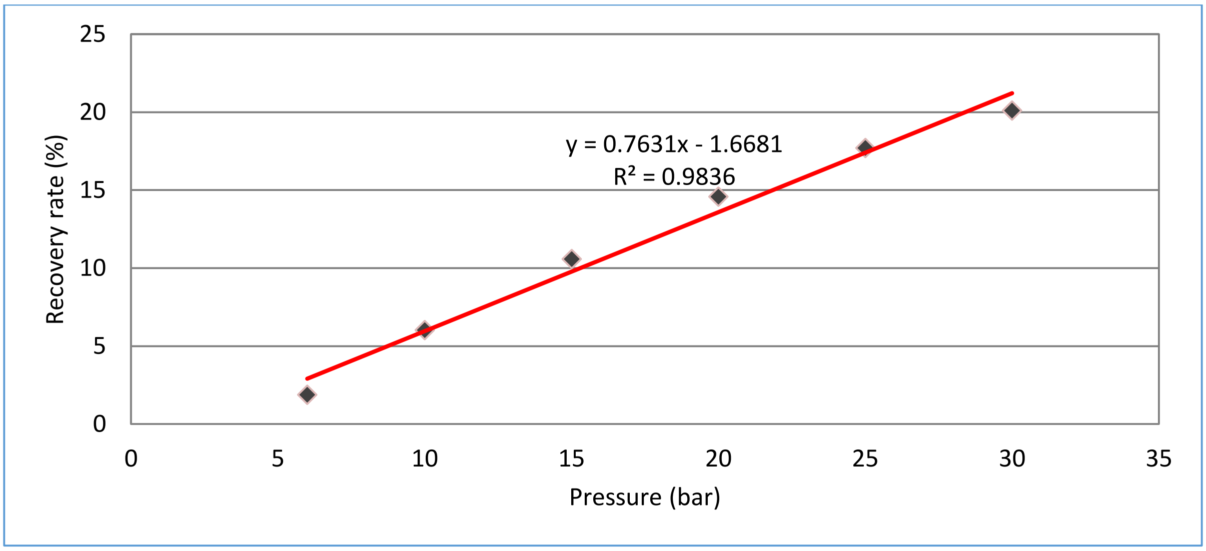


Figure (5-23): Effect of pressure on of recovery rate using one NF90 element in second pass desalination

5.5.2.3 Rejection Rate

i. TDS

Figure (5-24) shows the relationship between the rejection rate and pressures using one element of NF90 membrane. It is observed that rejection rate of the TDS increases sharply when the pressure changes from 6 to 10 bar, then it slightly increases with the pressure.

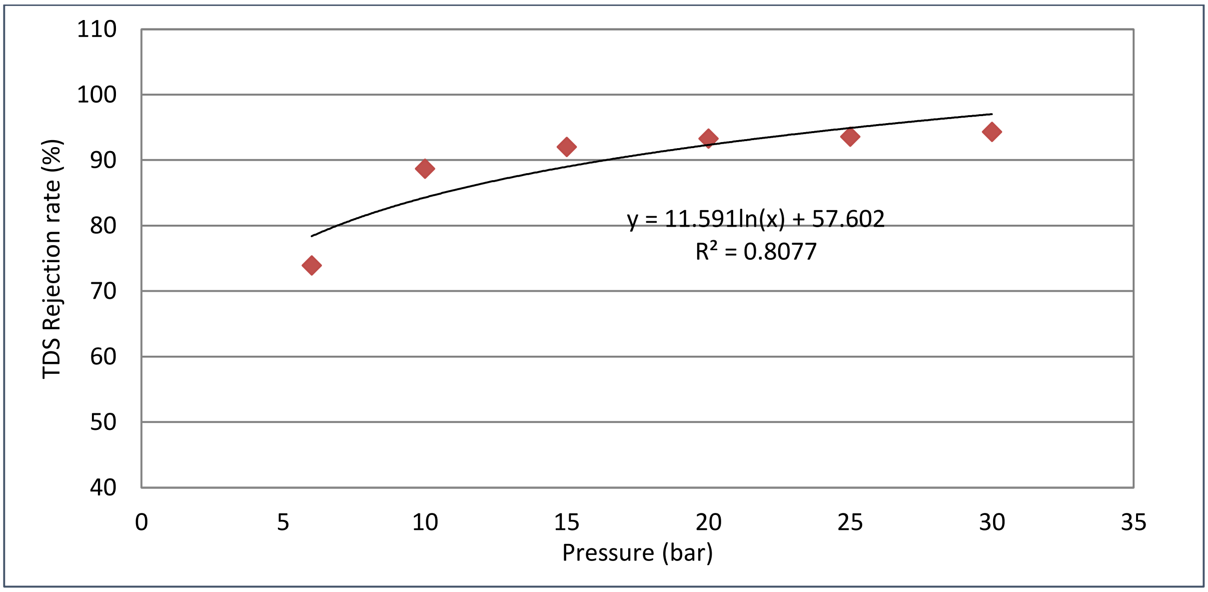


Figure (5-24): Effect of pressure on TDS rejection using one NF90 element in second pass desalination

ii. Chloride

Figure (5-25) shows the relationship between the chloride rejection rate and the pressures. It is observed that chloride rejection increases with the pressure. Actually, the chloride rejection sharply increases when the pressure arises from 6 to 10 bar, after that it slightly increases with pressure.

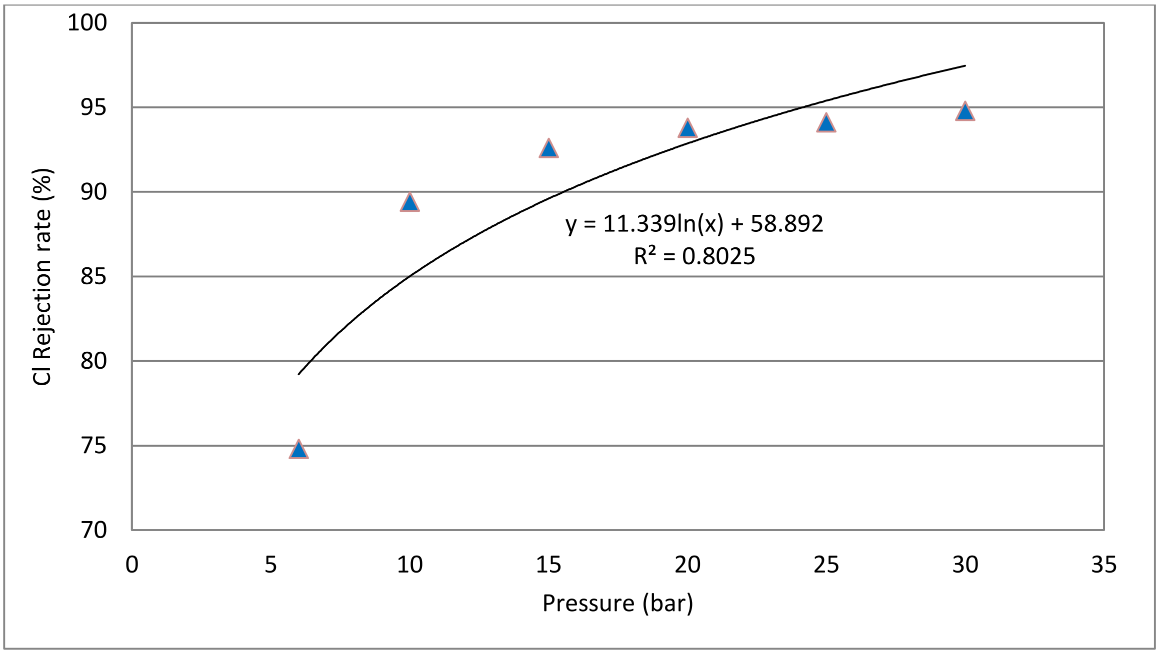


Figure (5-25): Effect of pressure on chloride rejection rate using one NF90 element in second pass desalination

The relationship between the ions rejection rate and the operating pressure for the other elements listed in table (4-3) are illustrated in appendix (3).

5.5.2.4 Remaining Ions

i. TDS

The effect of pressures on permeate TDS removal is shown in figure (5-26). The results show that when the pressure increases the TDS concentration decreases. However, the results showed that after pressure value of 10, the concentration of the TDS becomes less than (900 mg/l), which is acceptable for drinking purposes according to WHO standards (1000 mg/l).

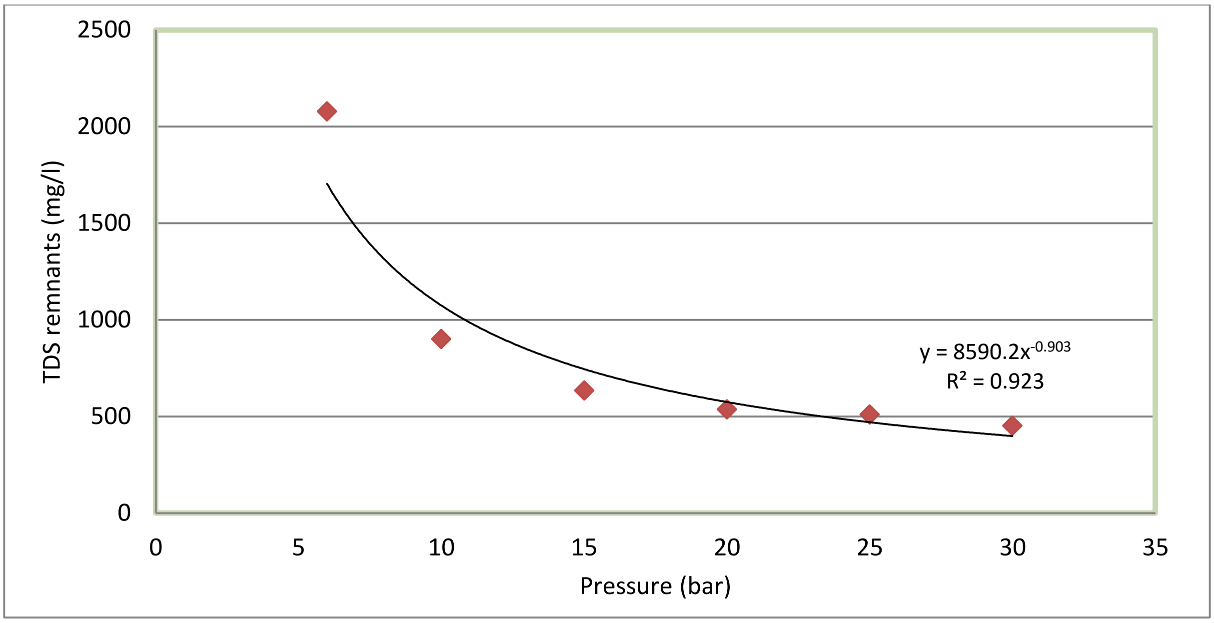


Figure (5-26): Effect of pressure on TDS removal using one NF90 element in second pass desalination

ii. Chloride

The effect of pressures on chloride removal is shown in figure (5-27). The result show that when pressure increases the chloride concentration decreases. However, after pressure of 25 bar, the chloride concentration is acceptable for drinking water according to WHO Standard (250 mg/l).

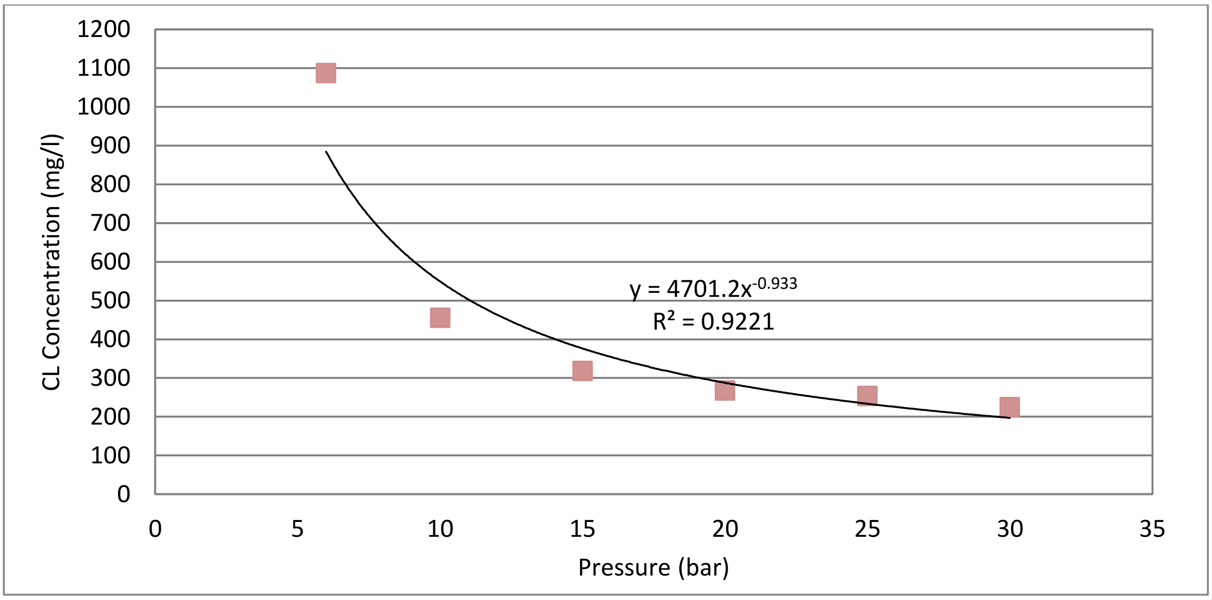


Figure (5-27): Effect of pressure on chloride removal using one NF90 element in second pass desalination

The relationship between the ions removal and the operating pressure for the other elements listed in table (4-3) are illustrated in appendix (3).

5.2.2.5 Specific Energy Consumption (SEC)

The relationship between the SEC of one cubic meter of permeate and pressure for one element NF90 is illustrated in figure (5-28). It is noted that SEC value decreases from (11.67 kWh/m^3) at 6 bar pressure to (4.16 kWh/m^3) at 15 bar. After 15 bar SEC value is almost stable with average of (5.23 kWh/m^3), that occurs because the SEC value is affected by change in pressure and recovery rate, see equation (4.7). It is important to mention that, although the pressure affects both of the recovery rate and the SEC, the recovery rate is much affected by pressure than the SEC.

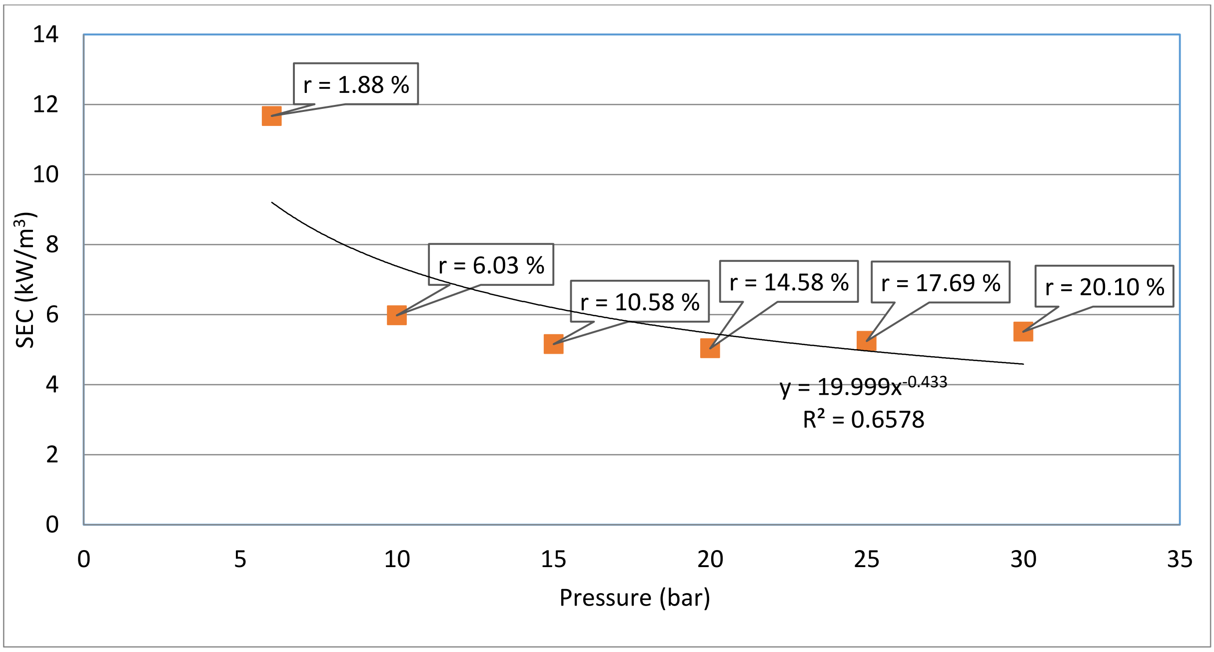


Figure (5-28): Relationship between energy consumption and pressure using one NF90 element in second pass desalination

5.2.2.6 Evaluation

From figure (5-13) in first pass desalination, at 37 bar pressure, the value of cumulative recovery rate of six NF90 elements in series is (34.75 %). And from figure (5-20) the value of SEC of one cubic meter of permeate is (3.72 Kw/m^3). Figure (5-28) shows the value of SEC for each pressure when using NF90 as a second pass. Table (5-2) shows the values of the SEC -for one cubic meter of permeate- obtained from the first pass of desalination at 37 bar pressure and the SEC values of the second pass of desalination at each used bar pressure as well as their sums. TDS and Cl concentrations in the permeate after two passes of desalination (NF90 membrane as first and second pass) are also illustrated in this table. This table also record the recovery rate values obtained via first pass of desalination at 37 bar pressure and the recovery rate values obtained via the second pass of desalination at each used bar pressure.

Table (5-2): Sums of SEC in two passes desalination and Cl concentration in product water at each used pressure

First pass: NF90 membrane				Second pass: NF90 membrane			Two passes (NF90 membrane & NF90 membrane)		
P (bar)	Cum. Y %	SEC (kW/m^3)	TDS (mg\l)	P (bar)	Y %	SEC (kW/m^3)	TDS (mg/l)	Cl (mg/l)	SEC (kW/m^3)
37	34.75	3.72	7971	6	1.88	11.67	2077	1087	15.39
37	34.75	3.72	7971	10	6.03	5.98	900	456	9.70
37	34.75	3.72	7971	15	10.58	5.16	634	319	8.87
37	34.75	3.72	7971	20	14.58	5.04	536	268	8.75
37	34.75	3.72	7971	25	17.69	5.25	510	254	8.96
37	34.75	3.72	7971	30	20.11	5.51	452	225	9.23

In this section of research, the choice of seawater desalination using NF90 membrane as a first pass, and NF90 membrane as a second pass is evaluated. The evaluation depends on the Cl concentration of permeate and SEC values obtained via the two passes. Figure (5-29) illustrates the relationship between the sum of SEC values in two passes of desalination and Cl concentration of permeate at each pressure value used in second pass.

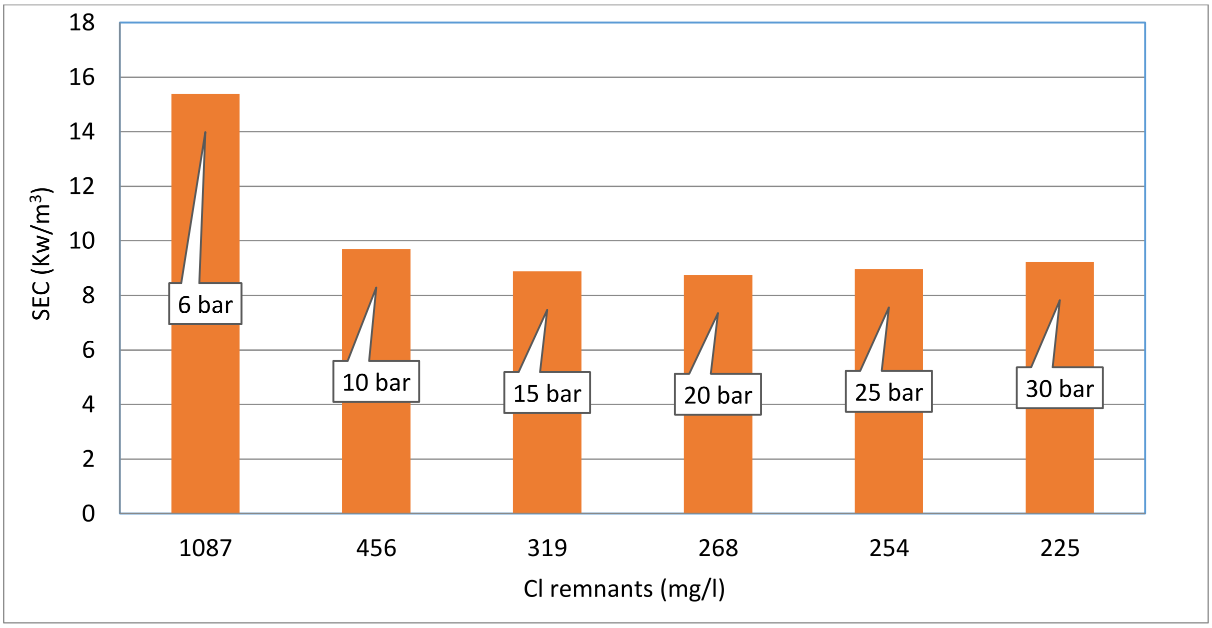


Figure (5-29): Relationship between sums of SEC in two passes desalination and Cl concentration in product water

Figure (5-29) shows that the acceptable chloride concentration - according to WHO standards for drinking water - only achieved at 30 bar pressure, which corresponds with SEC value of (9.23 kW/m^3). The high value of SEC refers to the usage of only one NF90 membrane in the second pass and accordingly, the recovery rate value is (20.10%). It is important to mention that, when more than one element are used in series the value of recovery rate will increase and the SEC will significantly decrease.

5.6 Fifth Package of Experiment: Second Pass Desalination using RO Brackish Water Membrane

In this package of experiments, the unit was operated using one element RO brackish water membrane and the permeate collected from the third package of experiments (at 37 bae pressure) used as a feed for the second pass of desalination. The experiments were carried out at pressures of 6, 10, 15, 20, 25 and 30 bars. For each experiment, the characteristics of permeate water were measured in terms of flux, recovery rate and rejection rate under the operating pressure values mentioned above as flow:

5.6.1 NaCl Solution (7109 mg/l)

A run using NaCl solution of (7109 mg/l) concentration was carried out using RO brackish water membrane to compare the obtained results with the results obtained from the other runs in this package .The same applied pressure values used in the NaCl solution experiment are used in the real water experiments. These values varied from 6 to 30 bar. In each run, the value of the flux rate of the solution was measured. Figure (5-30) shows the relationship between the flux rate and the pressure. It is noted that the flux rate increases linearly with the pressure.

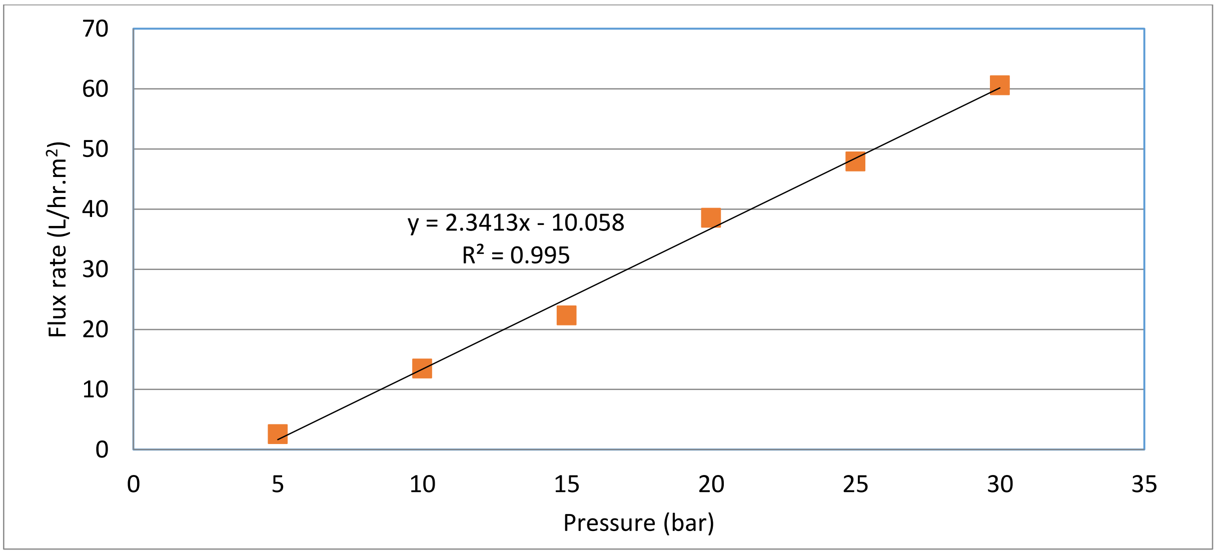


Figure (5-30): Relationship between the flux rate using (7109 mg/l) NaCl solution and the pressure for BW-2540 membrane

5.6.2 Real Water

5.6.2.1 Flux Rate and Hydraulic Permeability

Figure (5-31) shows the relationship between the flux rate and the pressure using RO brackish membrane fed by both NaCl solution (7109 mg/l) and real water (TDS concentration 7971.54 mg/l). The flux rate increases linearly with the pressure. It is observed that the flux rate of the real water is less than flux rate of the NaCl solution at all pressure values. The Lp of real water in second pass desalination is (1.8845 $L.h^{-1}.m^{-2}.bar^{-1}$) and its less than Lp when NaCl solution is used (2.3413 $L.h^{-1}.m^{-2}.bar^{-1}$), and that due to the presence of other ions in the real water.

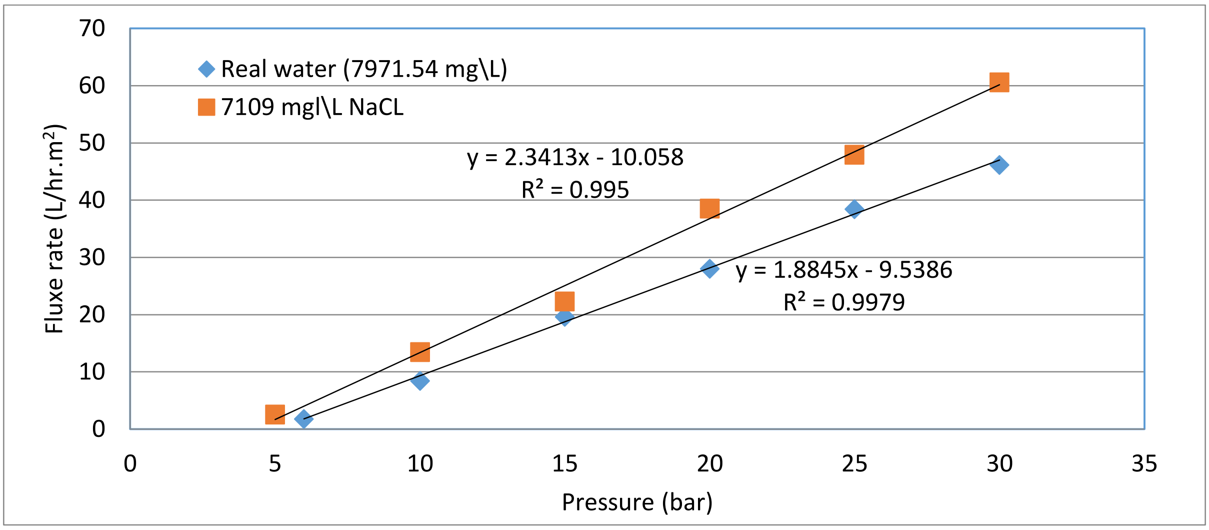


Figure (5-31): Relationship between the flux rate and the pressures using RO brackish water membrane

5.6.2.2 Recovery Rate

Figure (5-32) shows the relationship between the recovery rate and operating pressure for one RO brackish water membrane. It is noted that, the recovery rate increase linearly with the pressure.

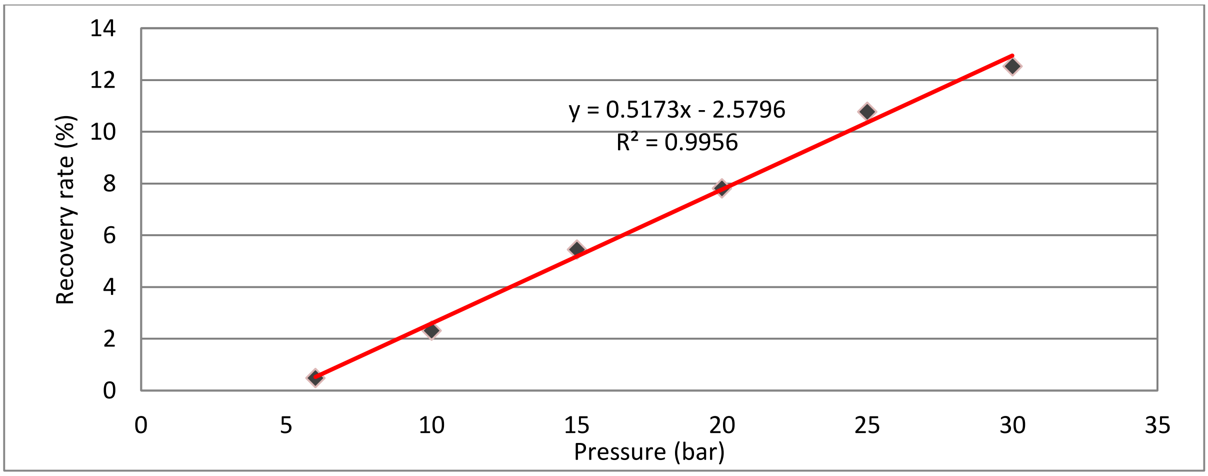


Figure (5-32): Effect of pressure on recovery rate using one RO brackish water membrane in second pass desalination

5.6.2.3 Rejection Rate

i. TDS

Figure (5-33) shows the relationship between the rejection rate and pressures using one element of RO brackish water membrane. It is observed that rejection rate of the TDS increases sharply when the pressure changes from 6 to 10 bar, then it slightly increases with the pressure.

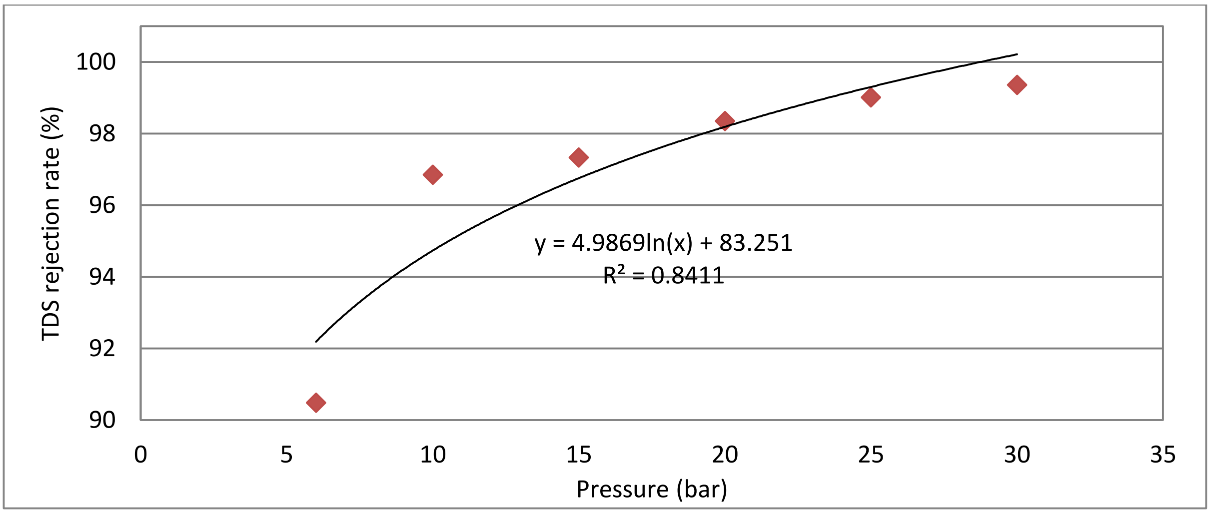


Figure (5-33): Effect of pressure on TDS rejection using one RO brackish water membrane in second pass desalination

ii. Chloride

Figure (5-34) shows the relationship between the chloride rejection rate and the pressures. It is observed that the chloride rejection increases with the pressure. Actually, the chloride rejection sharply increases when the pressure arises from 6 to 10 bar, after that it slightly increases

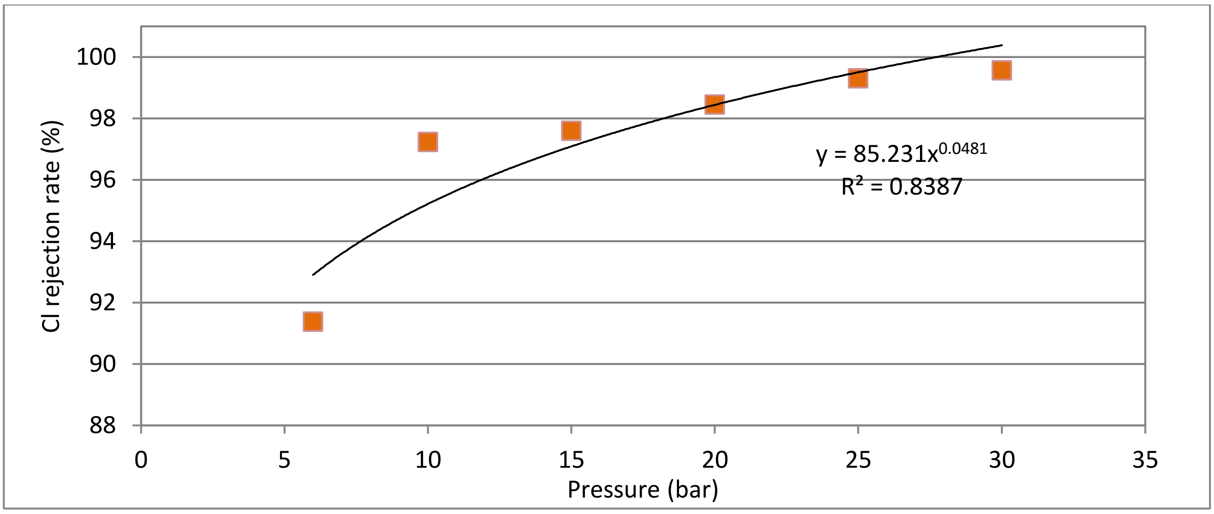


Figure (5-34): Effect of pressure on chloride rejection using one RO brackish water membrane in second pass desalination

The relationship between the ions rejection rate and the operating pressure for the other elements listed in table (4-3) are illustrated in appendix (4).

5.6.2.4 Remaining Ions

i. TDS

The effect of pressures on TDS removal is shown in figure (5-35). The results show that when the pressure increases the TDS concentration decreases. However, the results showed that after pressure value of 6, the concentration of the TDS becomes less than (840 mg/l), which is acceptable for drinking purposes according to WHO standards.

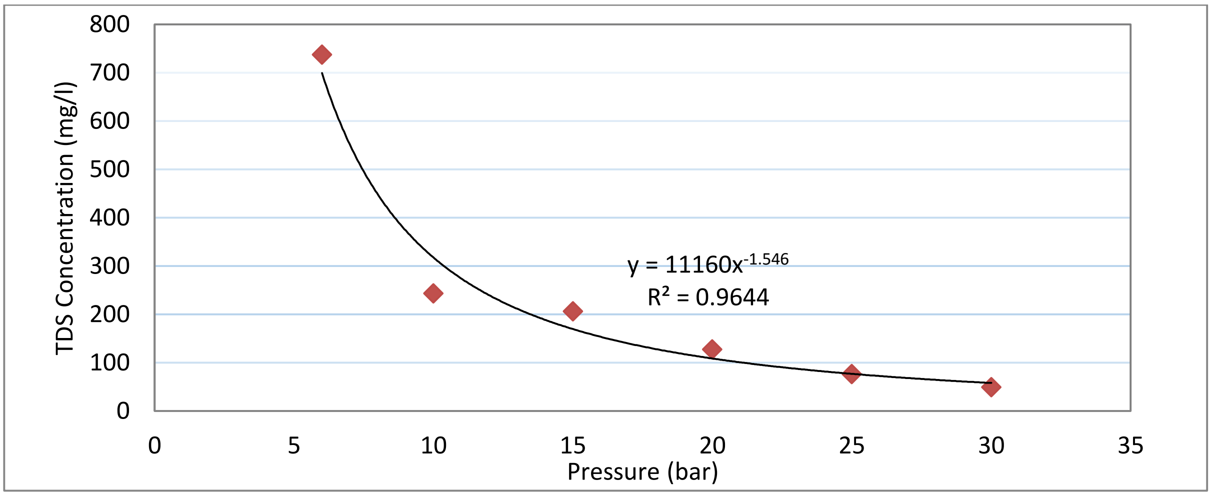


Figure (5-35): Effect of pressure on TDS removal using one RO brackish water membrane in second pass desalination

ii. Chloride

The effect of pressures on chloride removal is shown in figure (5-36). The result show that when pressure increases the chloride concentration decreases. However, after pressure of 10 bar, the chloride concentration is acceptable for drinking water according to WHO standard.

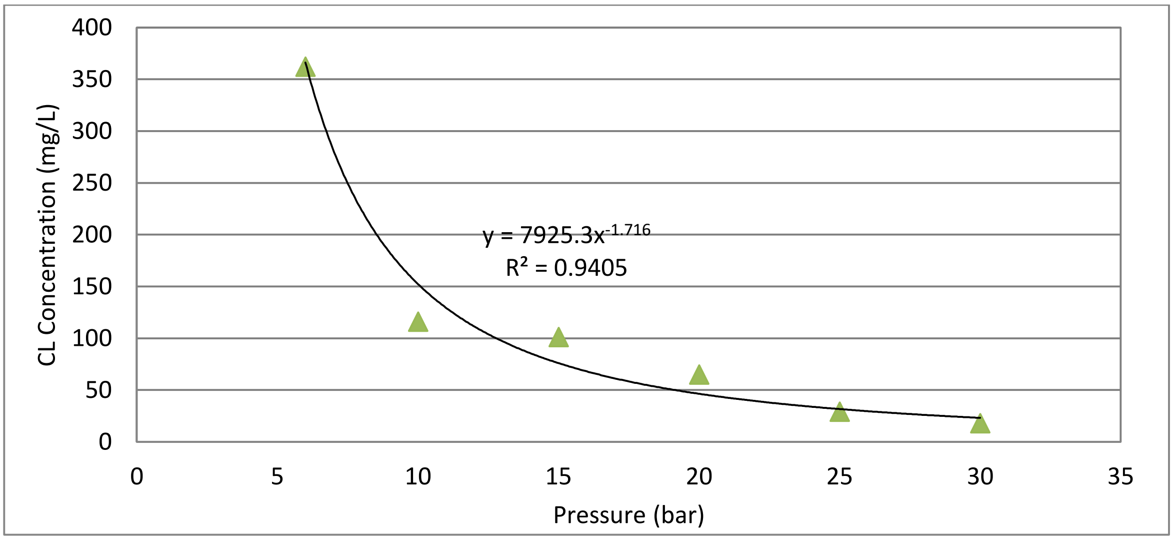


Figure (5-36): Effect of pressure on chloride removal using one RO brackish membrane element in second pass desalination

The relationship between the ions removal and the operating pressure for the other elements listed in table (4-3) are illustrated in appendix (4).

5.6.2.5 Specific Energy Consumption

The relationship between the SEC of one cubic meter of permeate and pressure for one element BW-2540 is illustrated in figure (5-37). It is noted that SEC value decreases from (44.20 kWh/m^3) at 6 bar pressure to (9.92 kWh/m^3) at 15 bar. After 15 bar, SEC value is almost stable with average of (9.02 kWh/m^3). That occurs because the SEC value is affected by change in pressure and recovery rate, see equation 3.7. Increase pressure lead to increase of recovery rate, which decreases the value of SEC.

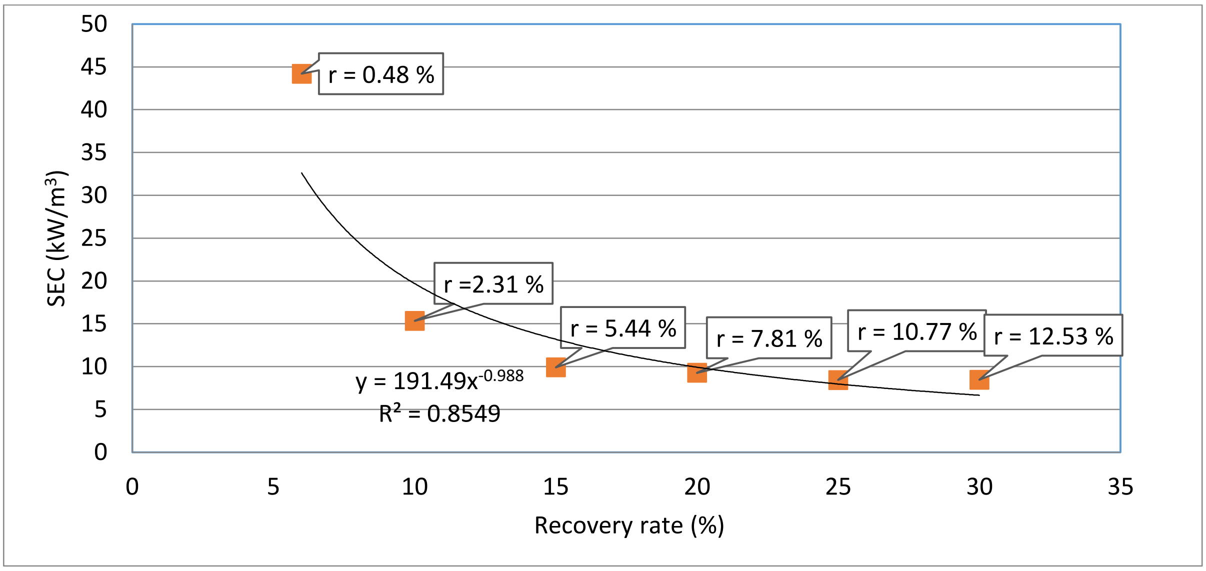


Figure (5-37): Relationship between energy consumption and pressure using one BW-2540 element in second pass desalination

5.6.2.6 Evaluation

From figure (5-13) in first pass desalination, at 37 bar pressure, the value of cumulative recovery rate of six NF90 elements in series is (34.75 %). And from figure (5-20) the value of SEC of one cubic meter of permeate is (3.72 Kw/m3). Figure (4-37) shows the value of SEC for each pressure when BW-2540 membrane is used as a second pass. Table (5-3) shows the values of the SEC -for one cubic meter of permeate- obtained from the first pass of desalination at 37 bar pressure and the SEC values of the second pass of desalination at each used bar pressure as well as their sums. TDS and CL concentrations after two passes of desalination (NF membrane as first pass and BW-2540 membrane as a second pass) are also illustrated in this table. This table also list the recovery rate values obtained via first pass of desalination at 37 bar pressure and the recovery rate values obtained via the second pass of desalination at each used bar pressure.

Table (5-3): Sums of SEC in two passes desalination and Cl concentration in product water at each used pressure

First pass: NF membrane				Second pass: RO brackish water membrane			Two passes (NF membrane & RO brackish water membrane)		
P (bar)	Cumulative Y %	SEC (kW/m^3)	TDS (mg\l)	P(bar)	Y %	SEC (kW/m^3)	TDS (mg/l)	Cl (mg/l)	SEC (kW/m^3)
37	34.75	3.72	7971	6	0.48	44.20	738	362	47.92
37	34.75	3.72	7971	10	2.32	15.33	244	116	19.05
37	34.75	3.72	7971	15	5.44	9.92	207	101	13.64
37	34.75	3.72	7971	20	7.81	9.28	128	65	12.99
37	34.75	3.72	7971	25	10.77	8.45	77	29	12.16
37	34.75	3.72	7971	30	12.53	8.46	50	18	12.17

In this section of research, the choice of seawater desalination using NF90 membrane as a first pass, and BW-2540 membrane as a second pass is evaluated. The evaluation depends on the Cl concentration of permeate and SEC values obtained via the two passes. Figure (5-38) illustrates the relationship between the sum of SEC values in two passes of desalination and Cl concentration of permeate at each pressure value used in second pass.

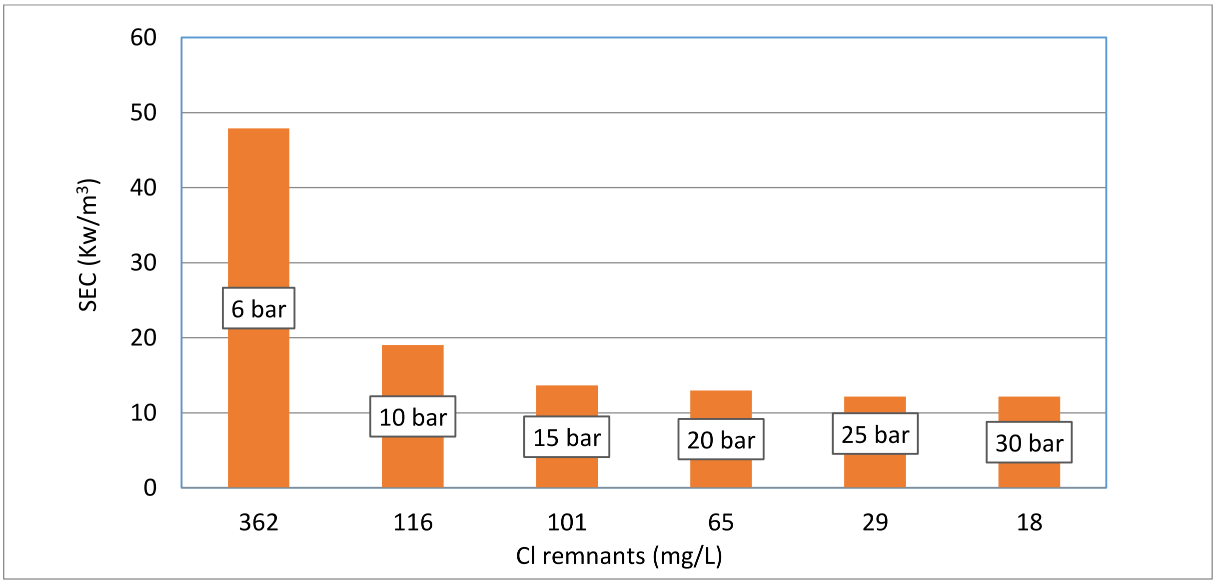


Figure (5-38): Relationship between sums of SEC in two passes of desalination and Cl concentration of product water

Figure (5-38) shows that although, after 10 bar presser all the Cl concentrations obtained are within the WHO standards for drinking water, the lowest SEC values obtained are 12.16 and 12.17 Kw/m^3 at pressure values of 25 and 30 bar respectively. The best choice was when 30 bar pressure is used in second pass of desalination, because at this pressure value, the recovery rate value is (12.53 %) which is higher than the recovery rate value of (10.77 %) corresponding with pressure value 25 bar. According to this choice, the number of membranes used inside one vessel for second pass desalination will be reduced.

5.7 Sixth Package of Experiments

In this package of experiments the raw seawater was desalinated using one RO seawater membrane element at operating pressures values of 37, 44, 51 and 60 bar. For each experiment, the characteristics of permeate water were measured in terms of flux, recovery rate and rejection rate under the operating pressure values mentioned above as flow:

5.7.1 Flux and Hydraulic Permeability

Figure (5-39) shows the relationship between the flux rate and the pressure using RO seawater membrane fed by both pure water and raw seawater (TDS concentration 36,850 mg/l). The flux rate increases linearly with the pressure. It is observed that the flux rate of the seawater is less than flux rate of the pure water at all pressure values. It is also noted that, the value of the Lp (0.7971 L.h^{-1}.m^{-2}.bar^{-1}) when using seawater which is less than the value of Lp (1.4484 L.h^{-1}.m^{-2}.bar^{-1}) when pure water is used, because of the presence of huge amounts of ions in seawater comparing with pure water.

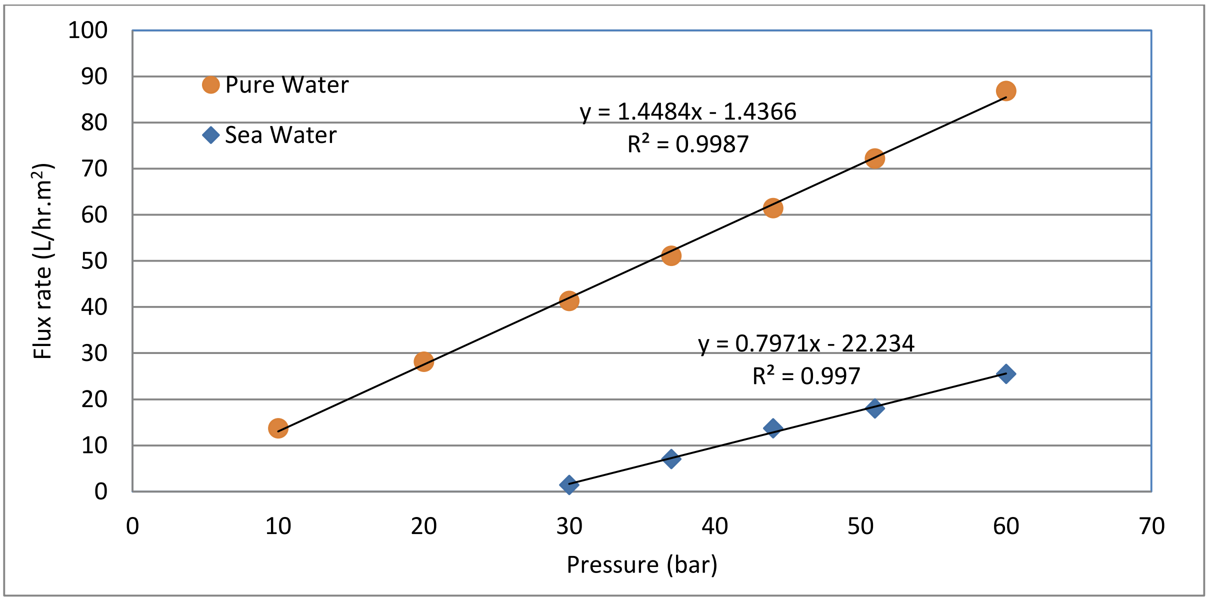


Figure (5-39): Relationship between flux rate using seawater or pure water and pressures using one RO seawater elements

5.7.2 Recovery Rate

Figure (5-40) shows the relationship between the recovery rate and operating pressure for one SW30 element. It is noted that, the recovery rate increase linearly with the pressure.

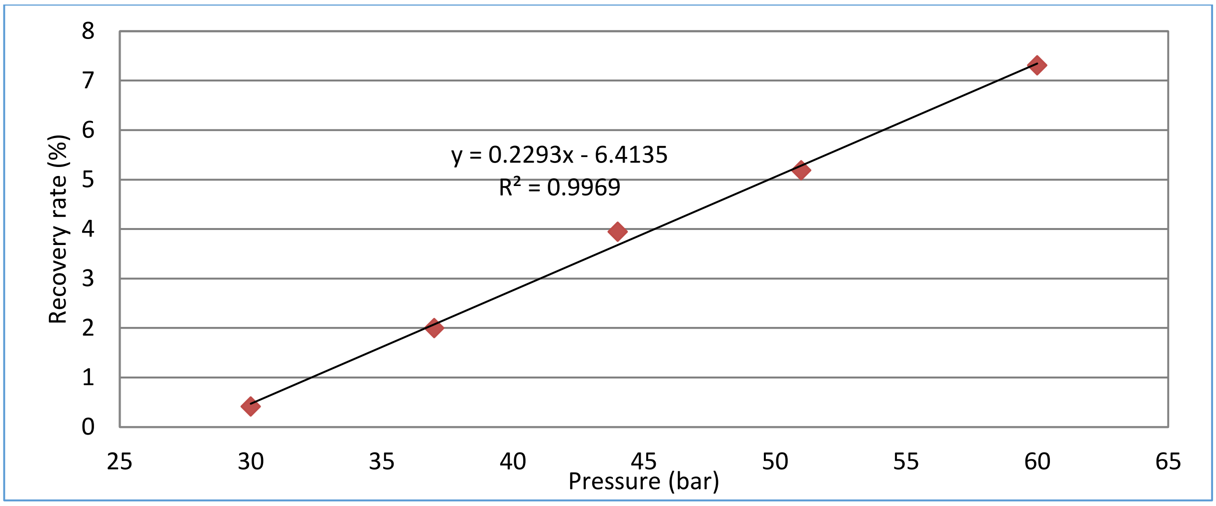


Figure (5-40): Effect of pressure on recovery rate in seawater desalination using one RO seawater membrane element

5.7.3 Rejection Rate

5.7.3.1 TDS and Chloride

Figure (5-41) shows the relationship between the rejection rate and pressures using one element of SW30 membrane for both TDS and Cl. It is observed that rejection rates of TDS and Cl increase with pressure. However, it is noted that there is no large differences between the values of the rejection rate that these values range from (99.26% and 99.12 %) to, (99.75 and 99.70 %) for TDS and Cl respectively. It is important to mention that, the highest recovery rate value (7.31%) was achieved at pressure value of 60 bar.

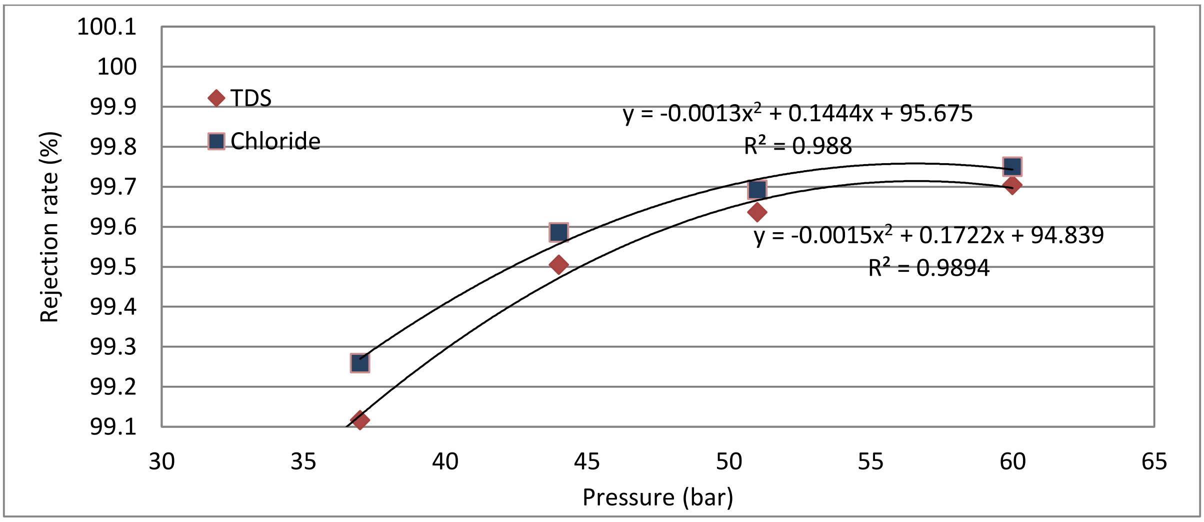


Figure (5-41): Effect of pressure on TDS and chloride rejection rate in seawater desalination using one RO seawater membrane

The relationship between the ions rejection rate and the operating pressure for the other elements listed in table (4-3) are illustrated in appendix (5).

5.7.4 Remaining Ions

5.7.4.1 TDS and Chloride

The effect of pressures on TDS and Cl removal is shown in figure (5-42). The results show that when the pressure increases the TDS and Cl concentration decreases. However, although the results showed that at all applied pressure values the obtained concentrations of the TDS and Cl are within the WHO standards for drinking water; the highest recovery rate value (7.31%) was achieved at pressure value of 60 bar.

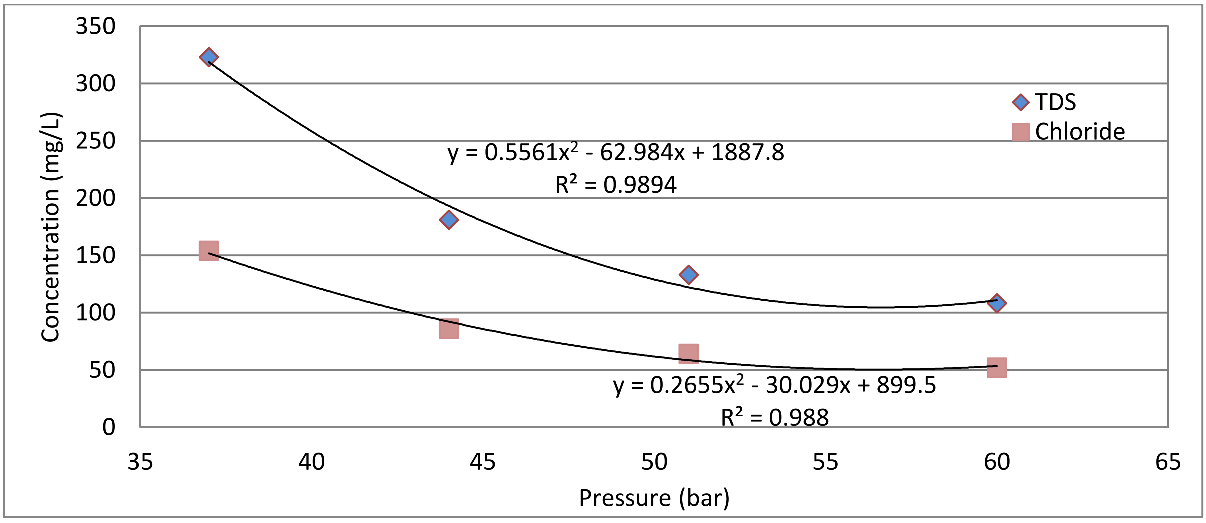


Figure (5-42): Effect of pressure on TDS and chloride removal in seawater desalination using one RO seawater membrane.

The relationship between the ions removal and the operating pressure for the other elements listed in table (4-3) are illustrated in appendix (5).

5.7.5 Specific Energy Consumption (SEC)

The relationship between the SEC of one cubic meter of permeate and pressure for one element SW30 is illustrated in figure (5-43). It is noted that SEC value decreases from (63.56 kWh/m^3) at 37 bar pressure to (28.57 kWh/m^3) at 60 bar. As a result of using only one SW30 element at 60 bar pressure, a low value of recovery rate obtained and accordingly, a high SEC value is achieved. Nevertheless, in case if six SW30 elements are used, the value of the recovery rate will be significantly increased and the value of the SEC will be decreased (as explained in next package of experiments).

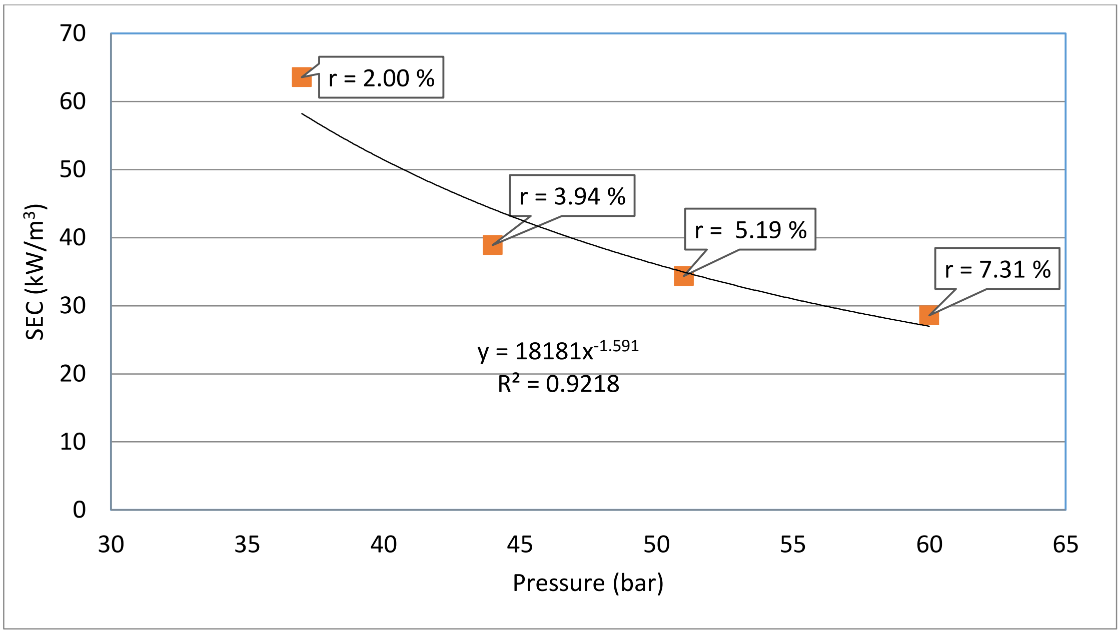


Figure (5-43): Relationship between energy consumption in seawater desalination and pressure using one RO seawater membrane

5.8 Seventh Package of Experiments

In this package, the unit was operated to desalinate sweater using six elements of SW30 membrane in series *without internal recirculation of the brine*. The brine of the first desalination run was collected in a separate tank and re-entered to the system as a feed water. This step was repeated for six times at a fixed pressure value of bar. The permeate was considered as a first pass desalination for the following second pass desalination. For each run; experimental data for the permeate flux, recovery rate, rejection rate and the ions concentration were obtained. In addition, for each run the concentration of the feed water of each one of the six membranes was calculated.

5.8.1 Flux

Figure (5-44) shows the relationship between the flux rate of the seawater and the elements' number for the six SW30 membranes. It is observed that the value of the flux rate of the first element is (25.50 L/hr.m^2). This value > that of the second element > third element > forth element > fifth element > sixth element (16.24 L/hr.m^2). The increase of flux rate resulted due to the increase of the TDS concentration of the feed. At 60 bar pressure, the TDS concentration of the feed of the first element is (36,580 mg/l), while, that of the sixth element is (51,862.30 mg/l), therefore the TDS concentration of the feed significantly influence the flux rate. In addition to that, even at small extent, the pressure drop lose from the first element to the sixth element influence the flux rate.

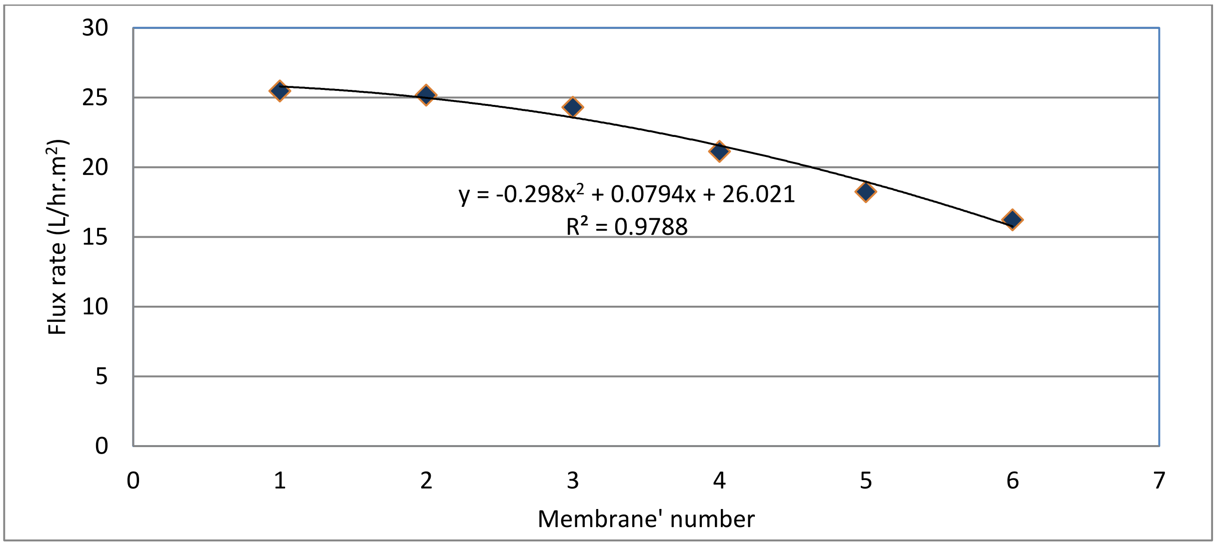


Figure (5-44): Relationship between the flux rate and elements' number using RO Seawater membrane in seawater desalination at 60 bar pressure

5.8.2 Recovery Rate

Figure (5-45) shows the relationship between the recovery rate of the seawater and the elements' number for the six SW30 membranes. It is observed that the value of the recovery rate of the first element is (7.31%). This value > that of the second element > third element > forth element > fifth element > sixth element (4.86%). The decrease in recovery rate refers to the same reasons mentioned in 4.8.1. Figure (5-46) shows the relationship between the cumulative recovery rate of the seawater and the number of used SW30 elements. The cumulative recovery rate linearly increase with the number of used SW30 elements. The cumulative recovery of the six elements in series is (38.72%).

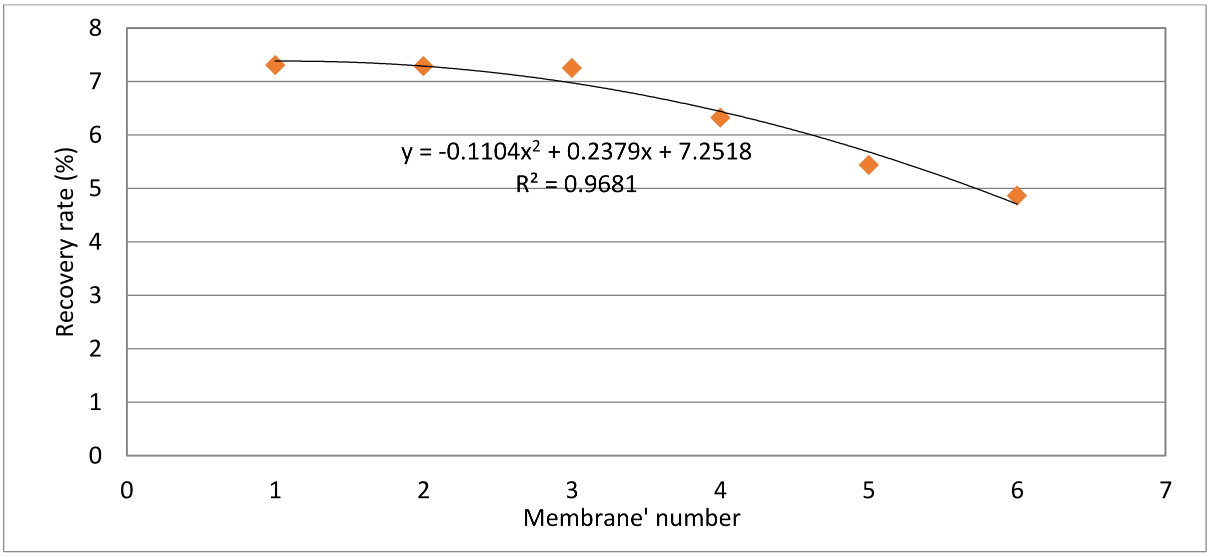


Figure (5-45): Relationship between recovery rate in seawater desalination and element' number at 60 bar pressure

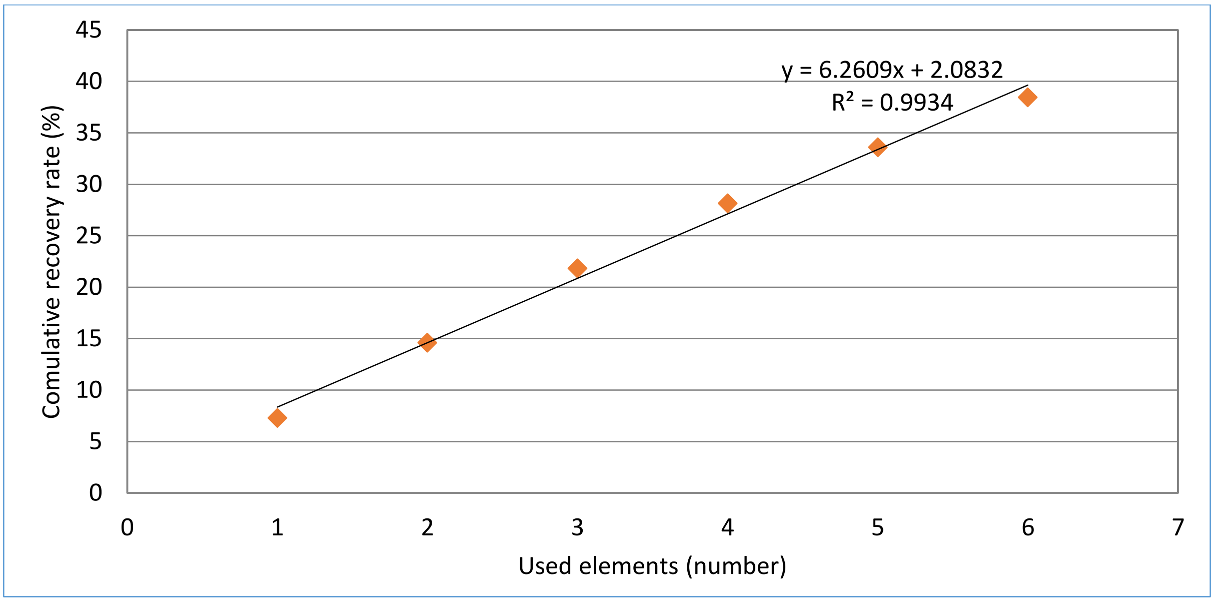


Figure (5-46): Relationship between the cumulative recovery rate in seawater desalination and the number of used elements at 60 bar pressure

5.8.3 Rejection Rate

5.8.3.1 TDS and Chloride

Figure (5-47) shows the relationship between the rejection rate and the SW30 elements' number for both TDS and Cl. It is observed that the values of the rejection rates of TDS and Cl in the first element are (99.70 % and 99.75%) respectively. These values > the values of the second element > the values of the third element > the values of the forth element > the values of the fifth element > the values of the sixth element (99.34% and 99.47 %) respectively. The decrease in rejection rate refers to the same reasons mentioned in 5.8.1.

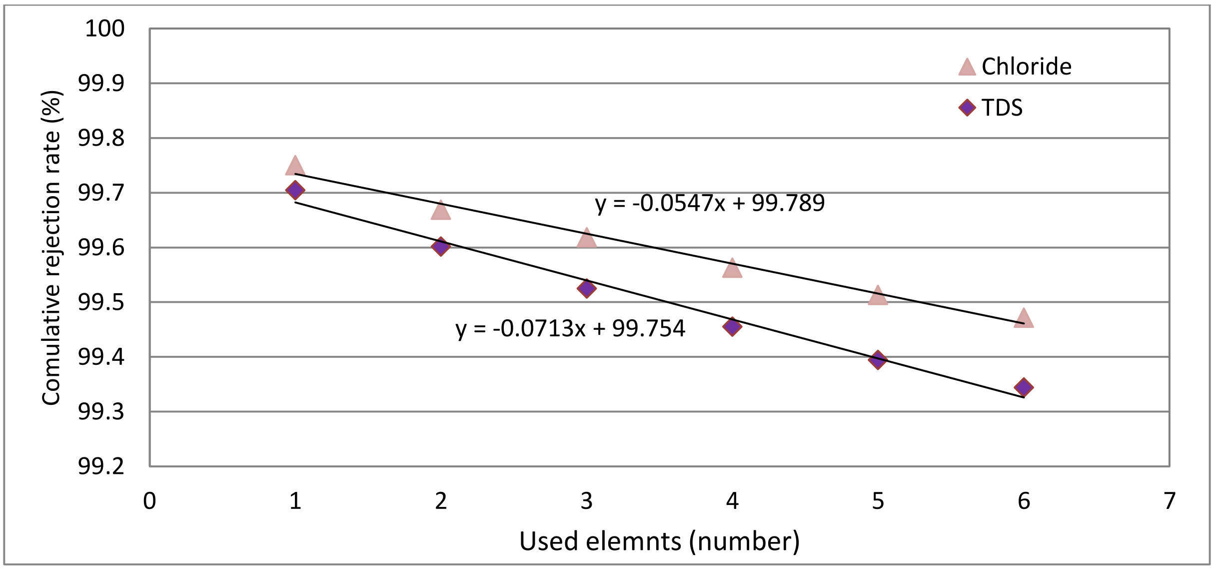


Figure (5-47): Relationship between number of used elements and cumulative rejection rate of TDS and chloride in seawater desalination

The relationship between the cumulative rejection rate and the number of used membranes for the other elements listed in table (4-3) are illustrated in appendix (6).

5.8.4 Remaining Ions

5.8.4.1 TDS and Chloride

Figure (5-48) shows the relationship between the cumulative concentration of TDS and CL in permeate and number of used SW30 elements. It is observed that the TDS and Cl concentrations increase with the increase of the number used elements due to the same reasons mentioned in 5.8.1.

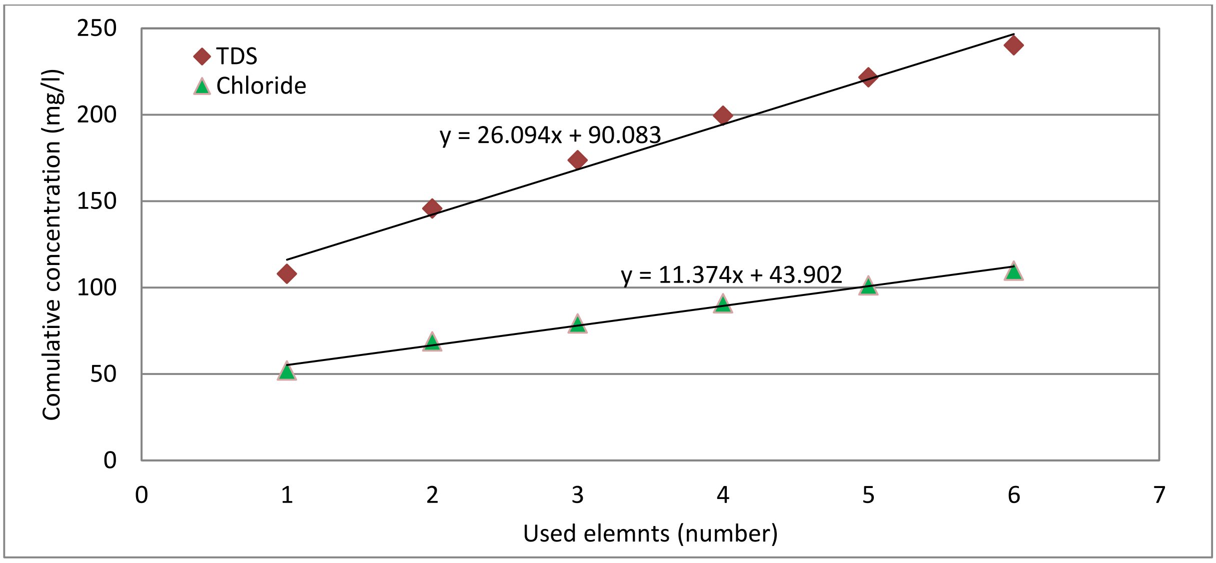


Figure (5-48): Relationship between number of used elements and cumulative TDS and chloride removal in seawater desalination

The relationship between the cumulative concentration and the number of used membranes for the other elements listed in table (5-3) are illustrated in appendix (6).

5.8.5 Specific Energy Consumption

The relationship between the SEC of one cubic meter of permeate and number of used SW30 element is illustrated in figure (5-43). The value of the SEC decrease with increase of the number of SW30 element used. It is noted that, when the number of used SW30 elements increases, the recovery rate increases and as a consequence, the SEC decreases. When six elements in series are used at 60 bar pressure, the value of the recovery rate is 38.46 % and accordingly the value of the SEC is (5.49 kWh/m^3), which is too much lower than the value of the SEC (28.58 kWh/m^3) when one element is used at pressure of 60 bar and recovery rate value of (7.31 %).

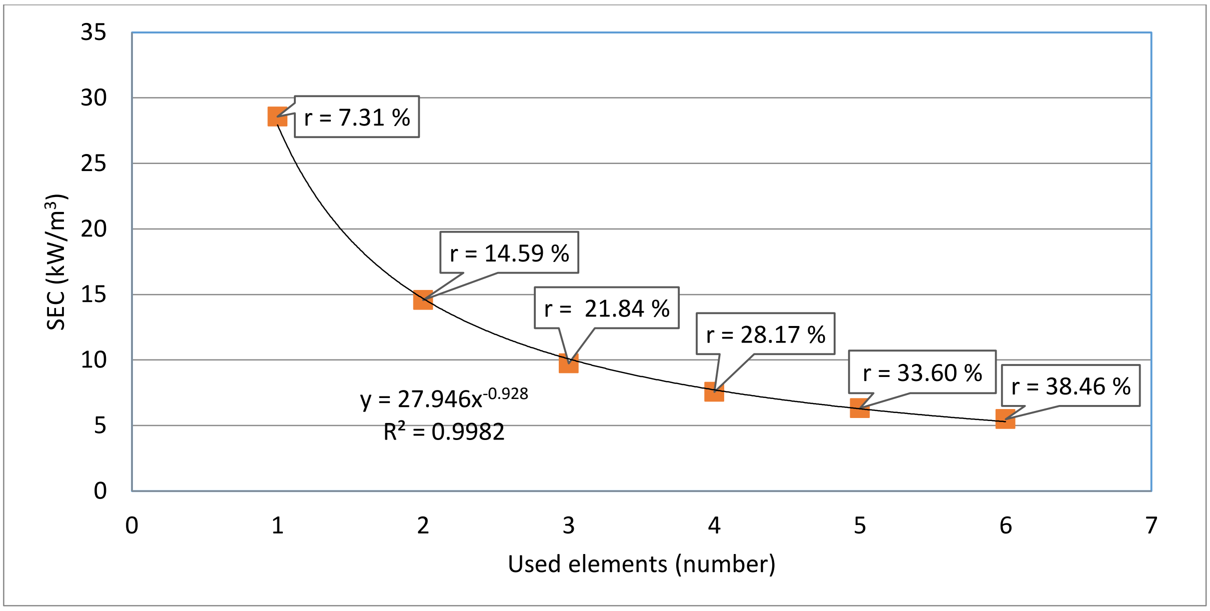


Figure (5-49): Relationship between SEC in seawater desalination and number of used elements at 60 bar pressure

5.9 Eighth Package of Experiments

In the previous package of experiments the permeate of desalination process at 60 bar pressure using six SW30 membranes in series was collected in a separate tank and considered as a first pass of desalination process. The characteristics of permeate are listed in table (5-4).

Table (5-4): Product water characteristics of first pass desalination using RO seawater membrane at 37 bar pressure

Element	Unit	Mem.1	Mem.2	Mem.3	Mem.4	Mem.5	Mem.6	Weighted Average
E.C	Micro mho/cm	175	296	374	5.82	547	596	387.83
TDS	mg/l	108	184	232	290	339	370	240.45
Chloride	mg/l as CL	52	86	101	132	156	170.30	110.04
Nitrate	mg/l as NO_3	0	0	0	0	0	0	0
Sulfate	mg/l as SO_4	0	0	0	0	0	0	0
Alkalinity	mg/l as CO_3	3	3	3	3	4	4	3.27
Hardness	mg/l as $CaCO_3$	10	9	12	11	12	13	11.01
Calcium	mg/l as Ca	0	0	0	0	0	0	0.00
Magnesium	mg/l as Mg	2	2	3	3	3	3	2.62
Potassium	mg/l as K	1.30	2.40	3.00	4.50	5.10	5.60	3.42
Sodium	mg/l as Na	24	46	61	78	98	110	65.04
Cadmium	µg/L as Cd	7.00	8.20	8.10	9.20	10.10	7.30	8.26
Copper	µg/L as Cu	20.00	17.1	16.2	12.3	11.1	13.2	15.39
Lead	µg/L as Pb	11.30	10.1	11.3	10.5	8.7	7.7	10.13

In this package of experiments, the unit was operated using one element NF membrane and the permeate collected in the previous package (at 60 bae pressure) used as a feed for the second pass of desalination. The experiments were carried out at pressures of 5, 10, 15, and 20 bars. For each experiment, the characteristics of permeate water were measured in terms of flux, recovery rate and rejection rate under the operating pressure values mentioned above as flow:

5.9.1 Second Pass with NF90 Membrane

5.9.1.1 Flux and Hydraulic Permeability:

Figure (5-50) shows the relationship between the flux rate and the pressure using NF90 membrane fed by both pure water and permeate collected in previous package (TDS concentration 240.45mg/l). The flux rate increases linearly with the pressure. It is observed that the flux rate of the collected permeate is less than the flux rate of the pure water at all pressure values. It is also noted that, the value of the Lp (3.6951 L.h^{-1}.m^{-2}.bar^{-1}) when collected permeate is used, which is less than the value of Lp (5.1281 L.h^{-1}.m^{-2}.bar^{-1}) when pure water is used, because of the presence of higher amounts of ions in collected permeate comparing with pure water.

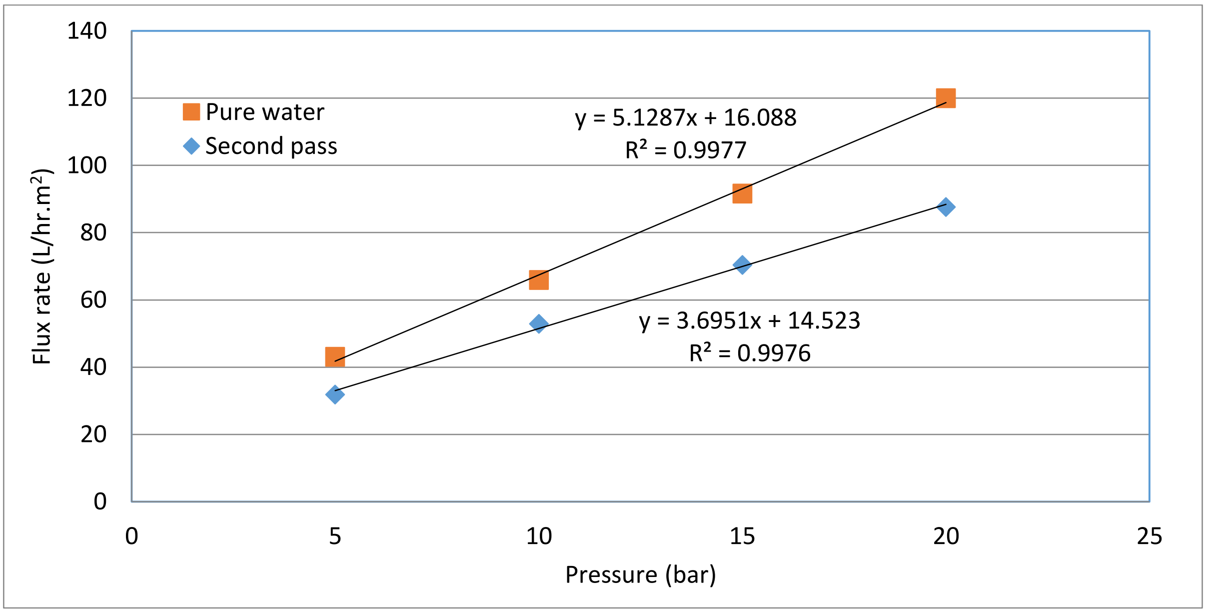


Figure (5-50): Relationship between pressure and flux rate using one NF elements in second pass desalination

5.9.1.2 Recovery Rate

Figure (5-51) shows the relationship between the recovery rate and operating pressure for one NF90 elements. It is noted that, the recovery rate increase linearly with the pressure.

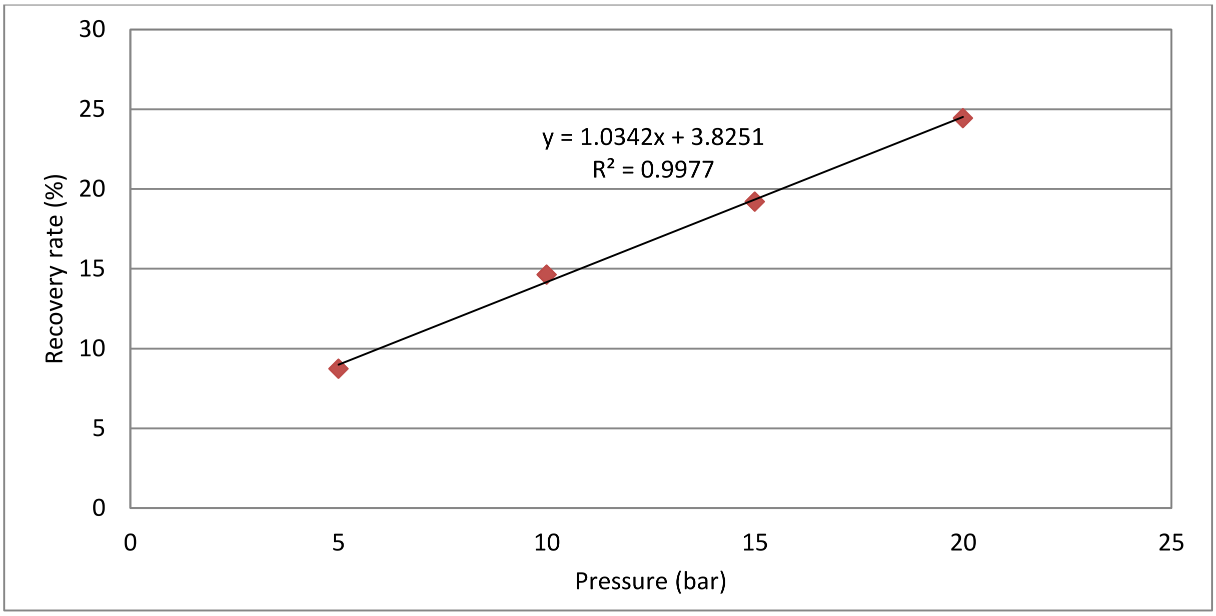


Figure (5-51): Relationship between recovery rate and the pressures using one NF90 element in second pass desalination

5.9.1.3 TDS and Cl removal

The effect of pressures on TDS and Cl removal is shown in figure (5-52). The results show that when the pressure increases the TDS and Cl concentration decreases. However, the results showed that at all applied pressure values the obtained concentrations of the TDS and Cl are within the WHO standards for drinking water.

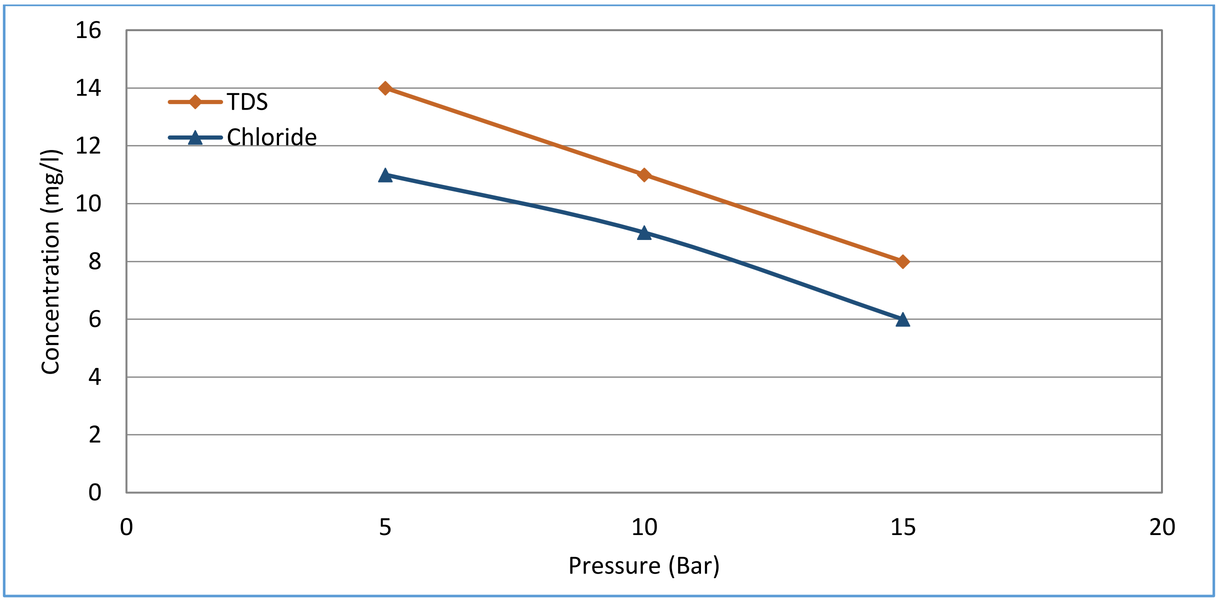


Figure (5-52): Effect of pressure on TDS and chloride removal using one NF90 element in second pass desalination

The relationship between the operating pressure and the concentrations other elements listed in table (4-3) are illustrated in appendix (7).

5.9.1.4 Specific Energy Consumption

The relationship between the SEC of one cubic meter of permeate and pressure for one element NF90 is illustrated in figure (5-52). It is noted that SEC value increases from (2.05kWh/m^3) at 6 bar pressure to (2.95 kWh/m^3) at 20 bar. That occurs because the SEC value is affected by change in pressure and recovery rate, see equation (4.7). It is important to mention that, although the pressure affects both of the recovery rate and the SEC, the SEC is much affected by pressure than the recovery rate.

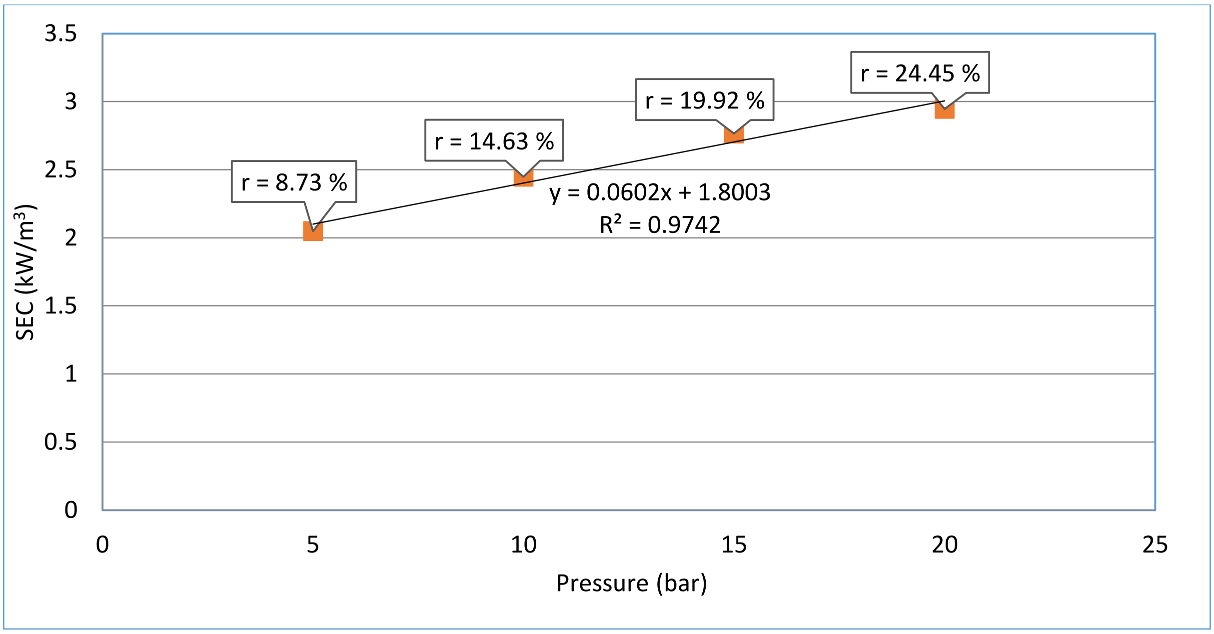


Figure (5-53): Relationship between energy consumption and pressure using one element NF90 in second pass desalination

5.9.1.5 Evaluation

From figure (5-46) in first pass desalination, at 60 bar pressure, the value of cumulative recovery rate of six SW30 elements in series is (38.46 %). And from figure (5-49) the value of SEC of one cubic meter of permeate is (5.43 Kw/m^3). Figure (5-53) shows the value of SEC for each pressure value when using NF90 as a second pass. Table (5-5) shows the values of the SEC -for one cubic meter of permeate- obtained from the first pass of desalination at 60 bar pressure and the SEC values of the second pass of desalination at each used bar pressure as well as their sums . TDS and Cl concentrations after two passes of desalination (SW30 membrane as first and NF90 as a second pass) are also illustrated in this table. This table also record the recovery rate values obtained via first pass of desalination at 60 bar pressure and the recovery rate values obtained via the second pass of desalination at each used bar pressure.

Table (5-5): Sums of SEC in two passes desalination and Cl concentration of product water at each used pressure

First pass (RO seawater membrane)				Second pass (NF membrane)			Two passes (RO seawater membrane & NF membrane)	
P (bar)	Cumulative Y (%)	SEC (kW/m^3)	TDS (mg\l)	P (bar)	Y (%)	SEC (kW/m^3)	Cl (mg/l)	SEC (kW/m^3)
60	38.46	5.49	240.45	5	8.73	2.04	10	7.54
60	38.46	5.49	240.45	10	14.63	2.45	10	7.94
60	38.46	5.49	240.45	15	19.21	2.77	8	8.26
60	38.46	5.49	240.45	20	24.45	2.95	6	8.44

In this section of research, the choice of sea water desalination using SW30 membrane as a first pass, and NF90 membrane as a second pass is evaluated. The evaluation depends on the Cl concentration of permeate and SEC values obtained via the two passes. Figure (5-54) illustrates the relationship between the sum of SEC values in two passes of desalination and Cl concentration of permeate at each pressure value used in second pass.

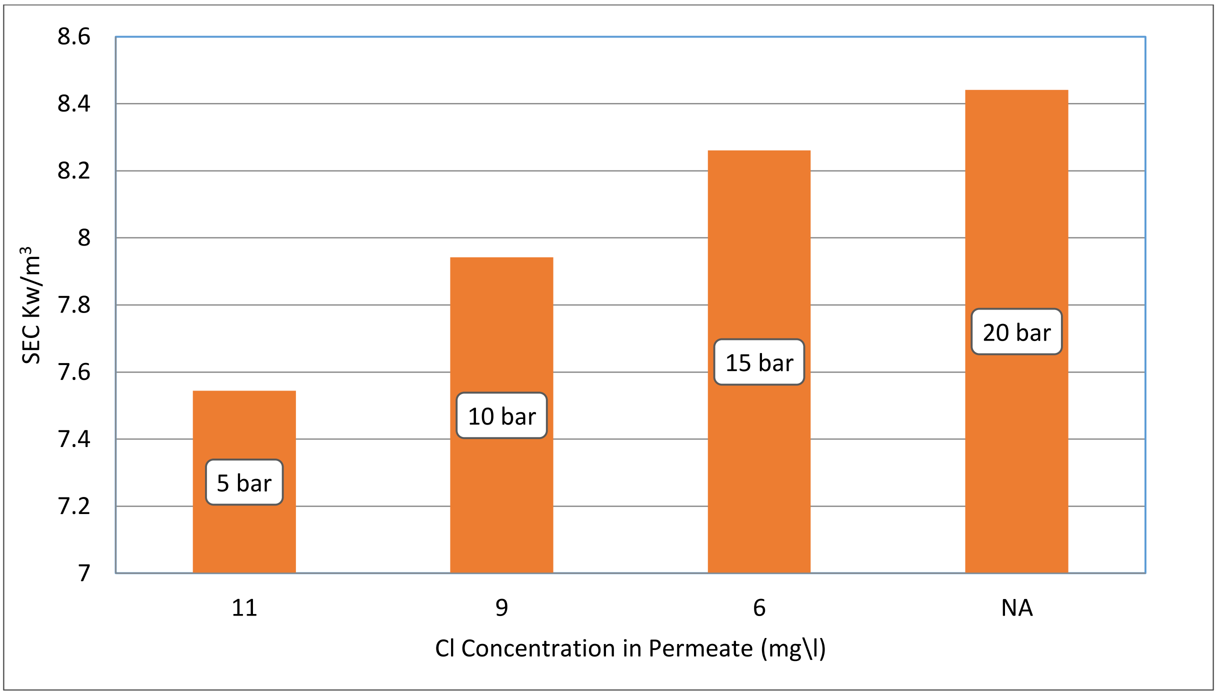


Figure (5-54): Relationship of Cl contaminate of product water and sums of SEC in two passes desalination

Figure (5-54) shows that, although, at all operating presser values all the Cl concentrations obtained are within the WHO standards for drinking water, the lowest SEC values obtained are is (7.54 and 7.94 Kw/m^3) at pressure values of 5 and 10 bar respectively. It is important to mention that, the recovery rate value at 5 bar is (8.73 %) and this value will be reduced when more than one elements in series are used. In addition to that, pressure drop lose through membranes and increases of TDS concentration of feed will reduce the recovery rate value too. In the other hand, at 10 bar pressure, recovery rate value is (14.63 %), this pressure value will be enough to cover pressure drop through membranes and produce acceptable recovery rate. So, the best choice was when 10 bar pressure is used in second pass of desalination, which corresponds with the SEC value of (7.94 Kw/m3). We note that this value of SEC is relatively high because we use one NF90 element in second pass, but when more than one NF90element are used the SEC value will be reduced.

5.9.2 Second Pass with RO Brackish Water Membrane

5.9.2.1 Flux and Hydraulic Permeability

Figure (5-55) shows the relationship between the flux rate and the pressure using RO Brackish water membrane fed by both pure water and permeate collected in previous package (TDS concentration 240.45mg/l). The flux rate increases linearly with the pressure. It is observed that the flux rate of the collected permeate is less than the flux rate of the pure water at all pressure values. It is also noted that, the value of the Lp (2.3408 $L.h^{-1}.m^{-2}.bar^{-1}$) when collected permeate is used, which is less than the value of Lp (2.9678 $L.h^{-1}.m^{-2}.bar^{-1}$) when pure water is used, because of the presence of higher amounts of ions in collected permeate comparing with pure water.

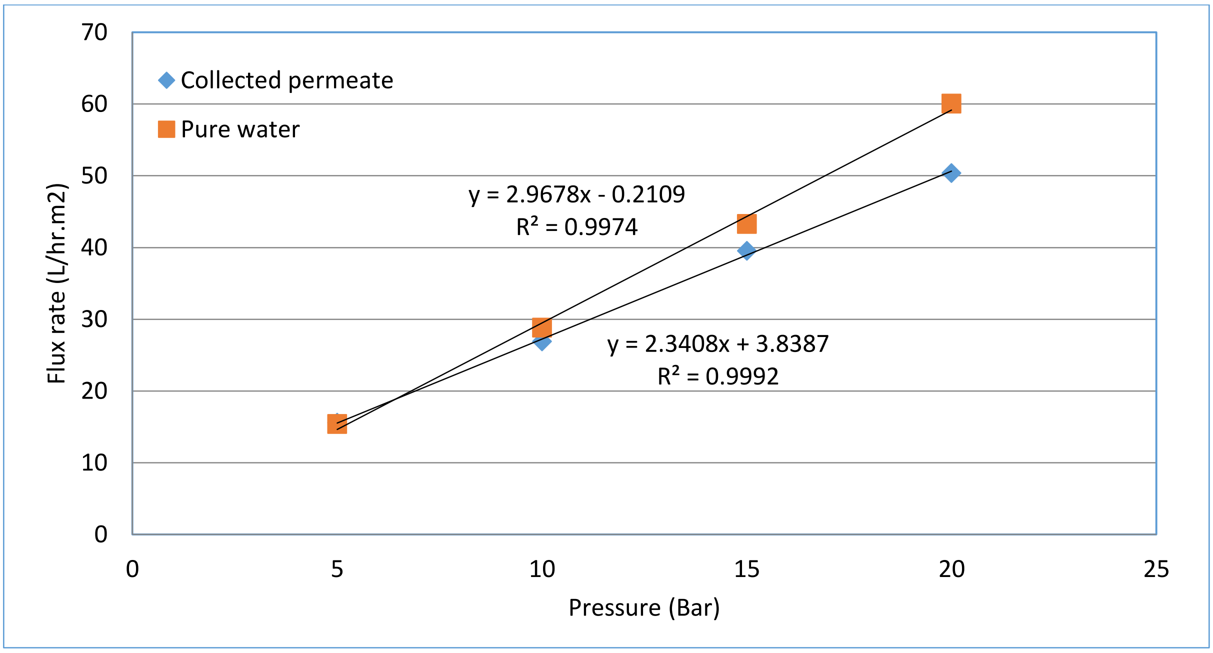


Figure (5-55): Relationships between the flux rate and the pressure using one RO brackish water membrane in second pass desalination

5.9.2.2 Recovery

Figure (5-56) shows the relationship between the recovery rate and operating pressure for one RO brackish water elements. It is noted that, the recovery rate increase linearly with the pressure.

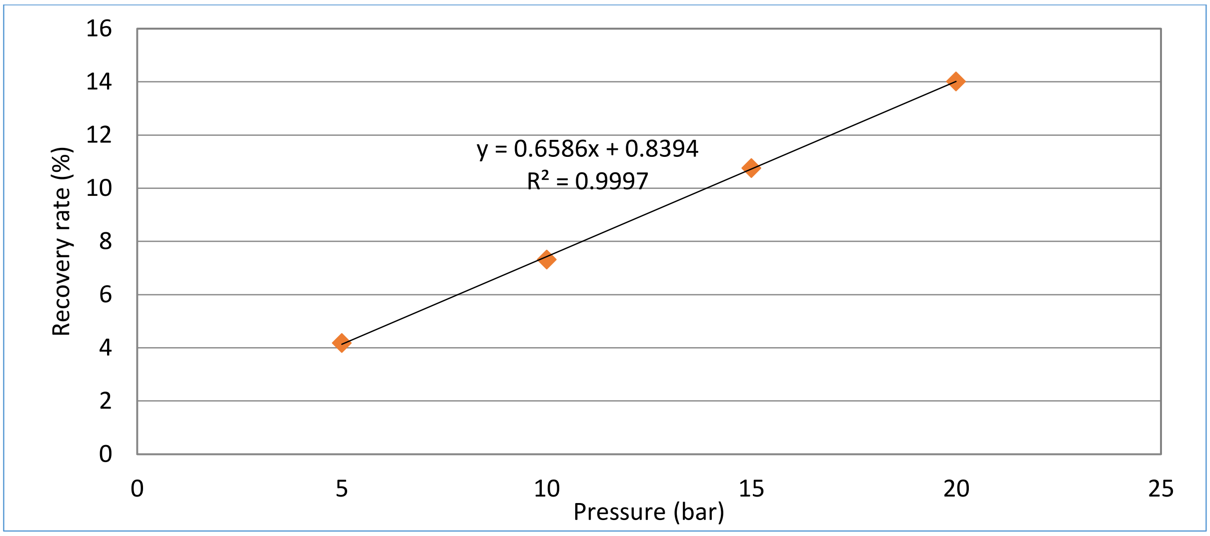


Figure (5-56): Effect of pressure on recovery rate using one RO brackish water in second pass desalination

4.9.2.3 Remaining: TDS and Chloride

The effect of pressures on TDS and Cl removal is shown in figure (5-57). The results show that when the pressure increases the TDS and Cl concentration decreases. However, the results showed that at all applied pressure values the obtained concentrations of the TDS and Cl are within the WHO standards for drinking water.

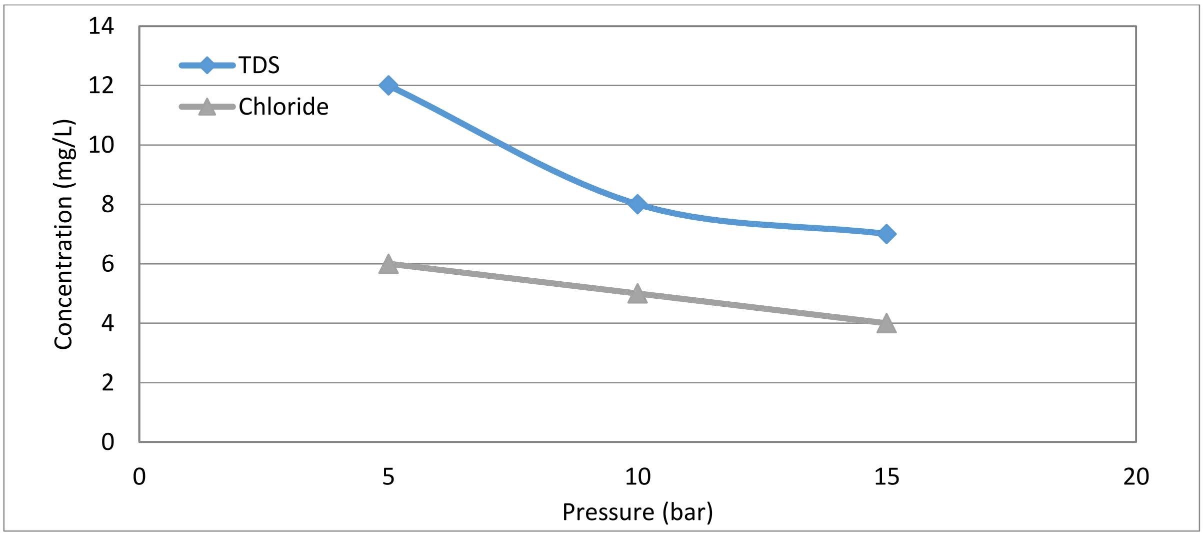


Figure (5-57): Effect of pressure on TDS and chloride removal using one RO brackish water in second pass desalination

The relationship between the operating pressure and the concentrations other elements listed in table (4-3) are illustrated in appendix (8).

4.9.2.4 Specific Energy Consumption

The relationship between the SEC of one cubic meter of permeate and pressure for one element BW-2540 is illustrated in figure (5-58). It is noted that SEC value increases from (4.20 kWh/m^3) at 6 bar pressure to (5.13 kWh/m^3) at 20 bar. That occurs because the SEC value is affected by change in pressure and recovery rate, see equation (4.7). It is important to mention that, although the pressure affects both of the recovery rate and the SEC, the SEC is much affected by pressure than the recovery rate.

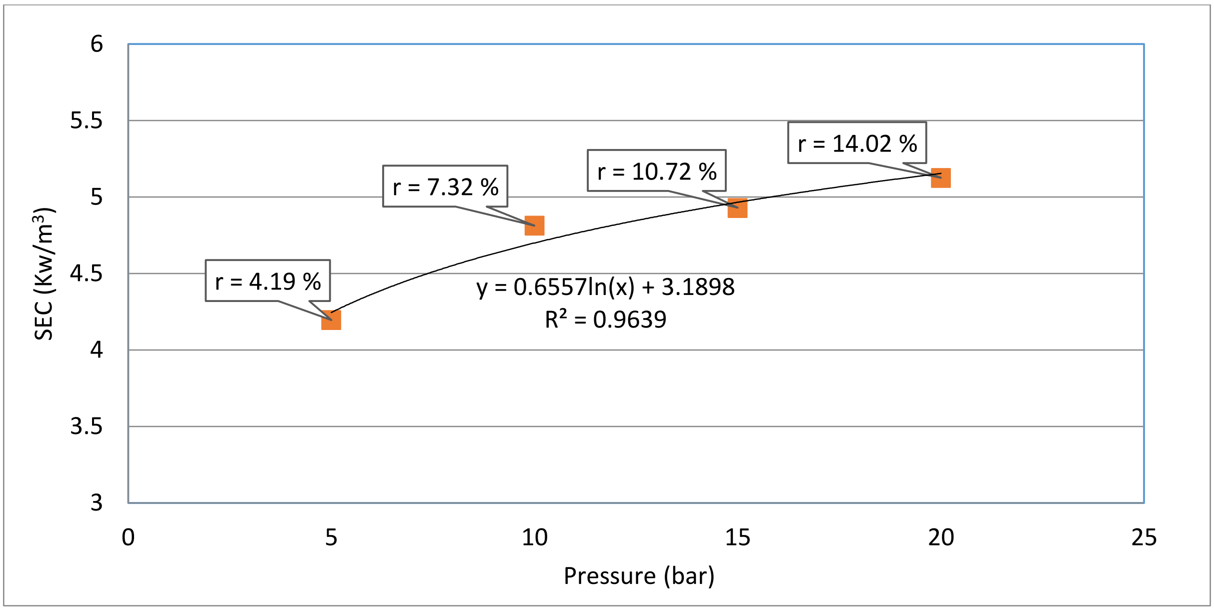


Figure (5-58): Relationship between energy consumption and pressure using one RO brackish water membrane in second pass desalination

5.9.2.5 Evaluation

From figure (5-46) in first pass desalination, at 60 bar pressure, the value of cumulative recovery rate of six SW30 elements in series is (38.46 %). And from figure (5-49) the value of SEC of one cubic meter of permeate is (5.43 Kw/m^3). Figure (5-58) shows the value of SEC for each pressure value when using BW-2540 as a second pass. Table (5-6) shows the values of the SEC -for one cubic meter of permeate- obtained from the first pass of desalination at 60 bar pressure and the SEC values of the second pass of desalination at each used bar pressure as well as their sums. TDS and Cl concentrations after two passes of desalination (SW30 membrane as first and BW-2540 as a second pass) are also illustrated in this table. This table also record the recovery rate values obtained via first pass of desalination at 60 bar pressure and the recovery rate values obtained via the second pass of desalination at each used bar pressure.

Table (5-6): Sums of SEC in two passes desalination and Cl concentration of product water at each used pressure

First pass (RO seawater membrane)				Second pass (RO brackish water membrane)			Two passes (RO seawater (membrane & NF membrane)	
P (bar)	cumulative Y %	SEC (kW/m^3)	TDS (mg\l)	P (bar)	Y (%)	SEC (kW/m^3)	Cl (mg/l)	SEC (kW/m^3)
60	38.46	5.49	240.45	5	4.19	4.19	6	9.69
60	38.46	5.49	240.45	10	7.32	4.81	5	10.31
60	38.46	5.49	240.45	15	10.76	4.93	4	10.42
60	38.46	5.49	240.4	20	24.45	2.95	NA	10.62

In this section of research, the choice of seawater desalination using SW30 membrane as a first pass, and BW-2540 membrane as a second pass is evaluated. The evaluation depends on the Cl concentration of permeate and SEC values obtained via the two passes. Figure (5-59) illustrates the relationship between the sum of SEC values in two passes of desalination and Cl concentration of permeate at each pressure value used in second pass.

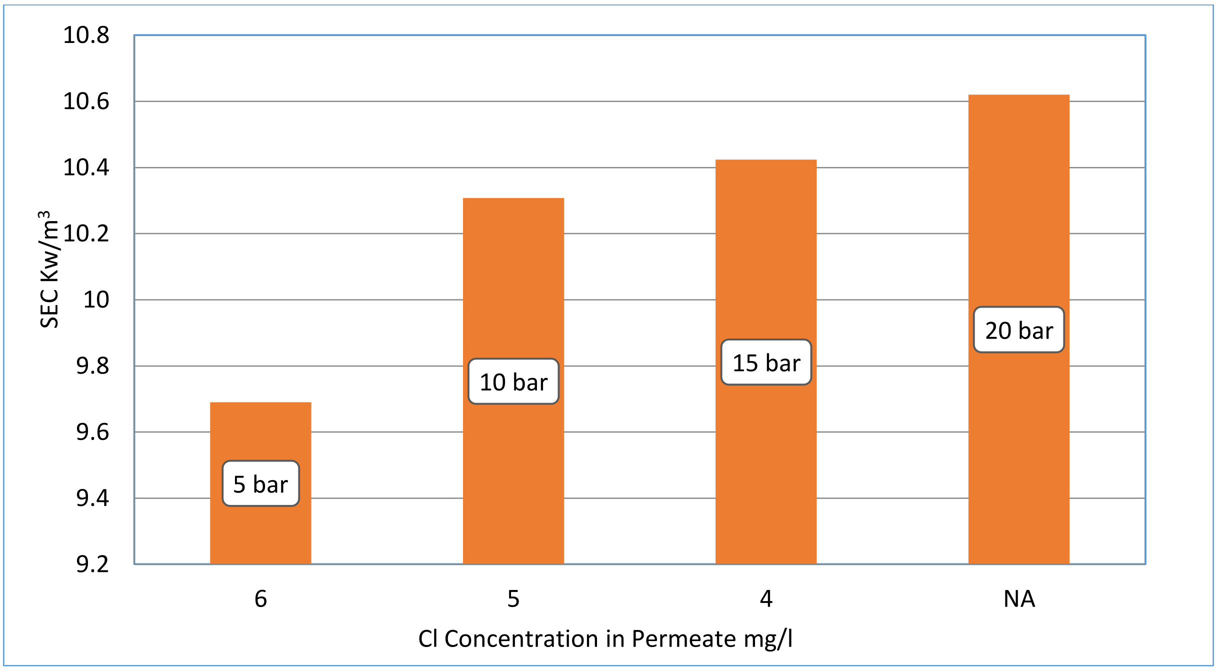


Figure (5-59): Relationship between sums of SEC in two passes desalination and Cl concentration of product water

Figure (5-59) shows that, although, at all operating presser values all the Cl concentrations obtained are within the WHO standards for drinking water, the lowest SEC values obtained are is 9.69 and 10.31 Kw/m^3 at pressure values of 5 and 10 bar respectively. It is important to mention that, the recovery rate value at 5 bar is (4.19 %), which is not enough to cover pressure drop through membranes and this value will be reduced when more than one elements in series are used. In addition to that, pressure drop lose through membranes and increases of TDS concentration of feed will reduce the recovery rate value too. In the other hand, at 10 bar pressure, recovery rate value is (7.32 %), this pressure value will be enough to cover pressure drop through membranes and produce acceptable recovery rate. So, the best choice was when 10 bar pressure is used in second pass of desalination, which corresponds with the SEC value of (10.31kW/m^3). We note that this value of SEC is relatively high because we use one BW-2540 element in second pass, but when more than one BW-2540 element are used the SEC value will be reduced.

5.10 Evaluation of Overall Seawater Desalinations Process

According to the evaluation of seawater desalination process discussed in previous section, four alternatives were chosen as the best choices. In this section, these four alternatives will be ordered according to the SEC value of one cubic meter of product water for two passes of desalinations for each alternative. Figure (5-60) illustrates the relationship between the SEC value and the variable combinations of used membranes.

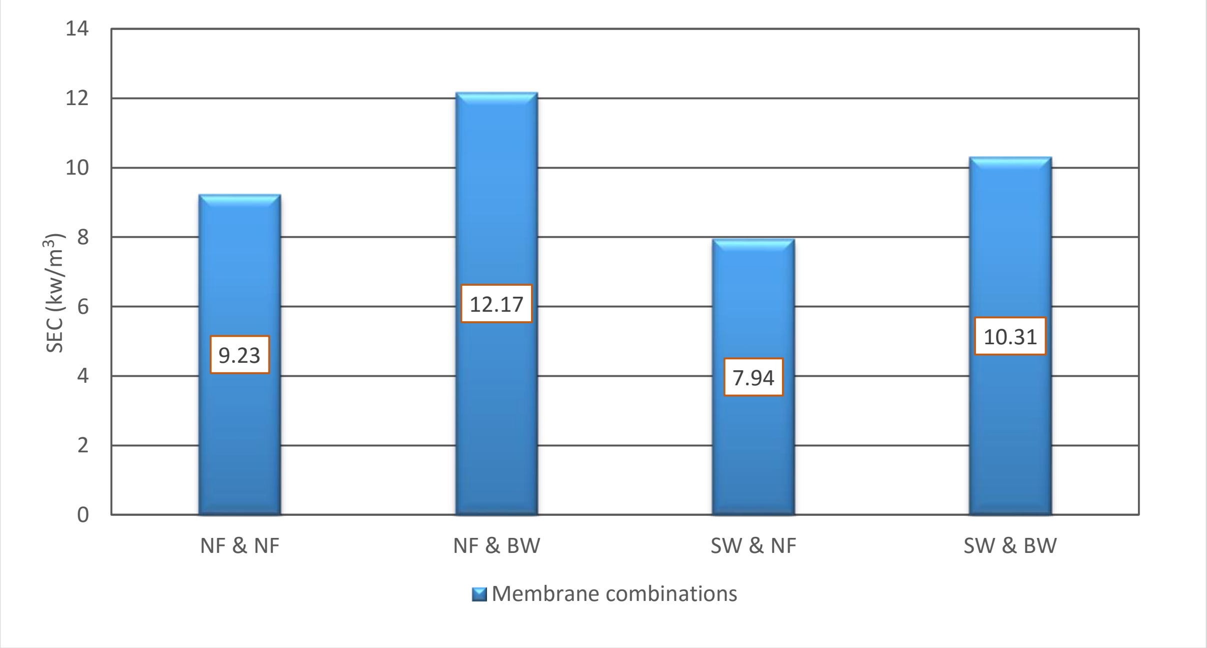


Figure (5-60): Relationship of SEC in two passes desalination and combination of used membranes

It is noted that, the best choice is to use RO seawater membrane as a first pass of desalination at pressure value of 60 bar, combined with NF membrane as a second pass of desalination at pressure value of 10 bar where, the corresponding SEC value (7.94 kW/m^3) is the lowest. The second choice is to use NF membrane for both first and second pass of desalination at pressure values of 37 and 30 bar respectively, where the SEC value is (9.23 kW/m^3). The third choice is to use RO seawater membrane as a first pass of desalination at pressure value of 60 bar combined with RO brackish water membrane as a second pass at pressure value of 10 bar which corresponds with SEC value of (10.31 kW/m^3). The last choice is to use NF membrane as a first pass at pressure value of 37 bar combined with RO brackish water membrane as a second pass at pressure value of 30 bar, where the SEC value is (12.17 kW/m^3) see table (5-7).

Table (5-7): Conclusion of two passes of sweater desalination

Membrane Combinations	Pressure (bar)		Recovery Rate (%)		Cl Concentration in permeate (mg/l)	SEC in two passes (kW/m^3)
	First Pass	Second Pass	First Pass (Six mem. in series)	Second Pass (One mem.)		
RO & NF	60	10	38.46	14.63	10	7.94
NF & NF	37	30	34.75	20.11	225	9.23
RO & BW	60	10	38.46	7.32	5	10.31
NF & RO	37	30	34.75	12.53	18	12.17

CAHPTER SIX: CONCLUSIONS AND RECOMMENDATIOS

6.1 Conclusions

1- For NF membrane, the effect of brine recirculation on flux rate, rejection rate and ions removal only occurs at higher values of applied pressure (30 and 37 bar). When using one element, at 37-bar pressure with (87%) brine recirculation ratio, the value of recovery rate obtained is (30.91%) and the TDS concentration value is (9074 mg/l). These values are equivalent to the recovery rate value obtained but less than the value of the TDS concentration (7611 mg/l) when fife elements in series are used although after brine recirculation ratio of (80%) the clogging problems appear.

2- For NF membrane, in first pass of seawater desalination the best results were achieved when applying pressure value of 37 bar, where, the cumulative recovery rate of six membranes in series is (34.75 %), TDS concentration is (7971.54 mg/l) and the SEC value is (3.72 kW/m^3). While in a second pass of seawater desalination using one NF element, the acceptable results were achieved only when 30 bar pressure was applied. Because at this pressure value the obtained Cl concentration is (225 mg/l) – within WHO standards for drinking water–, the recovery rate value is (20.10 %) and the SEC value is (5.51kW/m^3) taking into account that, the SEC value of the two passes of seawater desalination is (9.23 kW/m^3).

3- In other hand, when using one element RO brackish water membrane as a second pass of seawater desalination instead of NF membrane, the best recovery rate (12.53 %) was achieved when applying pressure value of 30 bar. At this pressure value the Cl concentration is (18 mg/l), and SEC value is (8.46kW/m^3) taking into account that the SEC value of the two passes of seawater desalination is (12.17 kW/m^3).

4- For RO seawater membrane, in first pass of seawater desalination the best results were achieved when applying pressure value of 60 bar, where, the cumulative recovery rate of six membranes in series is (38.46 %), the TDS concentration is (240.45 mg/l) and the SEC value is (5.49 kW/m^3). While in a second pass of seawater desalination using one NF element, the best results were achieved when 10 bar pressure was applied. Because at this pressure value the obtained Cl concentration is (10 mg/l), the recovery rate value is (14.63 %) and the SEC value is (2.45 kW/m^3) taking into account that, the SEC value of the two passes of seawater desalination is (7.94 kW/m^3).

5- When using one element RO brackish water membrane as a second pass of seawater desalination instead of NF membrane, the best recovery rate (7.32 %) was achieved when applying pressure value of 10 bar. At this pressure value the Cl concentration is (5 mg/l), and SEC value is (4.81kW/m^3) taking into account that the SEC value of the two passes of seawater desalination is (10.31 kW/m^3).

6- According to the SEC value obtained from each variable combination of used membranes, the best combination between membranes are ordered as follow:

(i) To use RO seawater membrane as a first pass of seawater desalination at pressure value of 60 bar combined with NF membrane as a second pass of seawater desalination at pressure value of 10 bar.

(ii) To use NF membrane for both first and second pass of seawater desalination at pressure values of 37 and 30 bar respectively.

(iii) To use RO seawater membrane as a first pass of seawater desalination at pressure value of 60 bar combined with RO brackish water membrane as a second pass at pressure value of 10 bar.

(iv) To use NF membrane as a first pass of seawater desalination at pressure value of 37 bar combined with RO brackish water membrane as a second pass of seawater desalination at pressure value of 30 bar.

6.2 Recommendations

1- Brine recirculation should be used (not more than 80%) in seawater desalination process.

2- NF membrane should be used in second pass of seawater desalination

3- More research should be carried out on second pass of seawater desalination using six membranes in series.

4- A pilot research unit should be installed in seawater desalination plant in Gaza Strip, where most of research requirements are available.

5- Membrane clogging should be more investigated.

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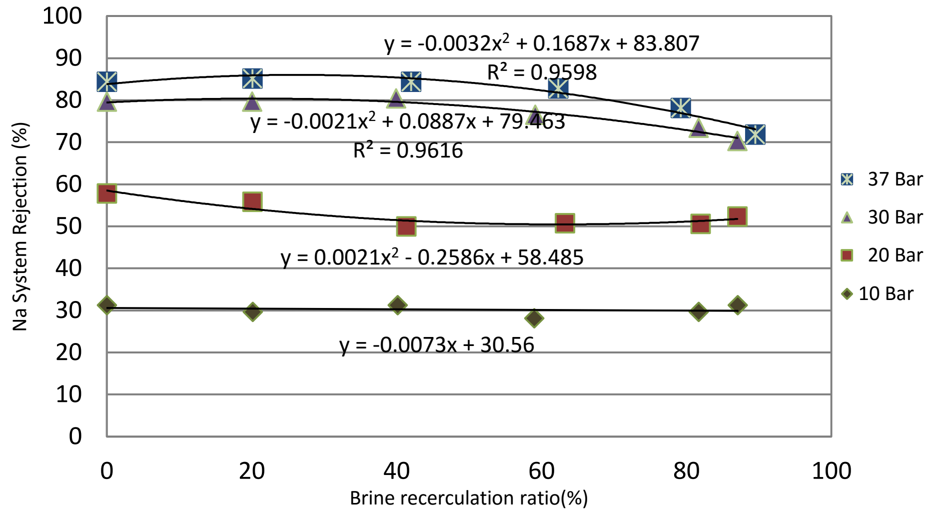
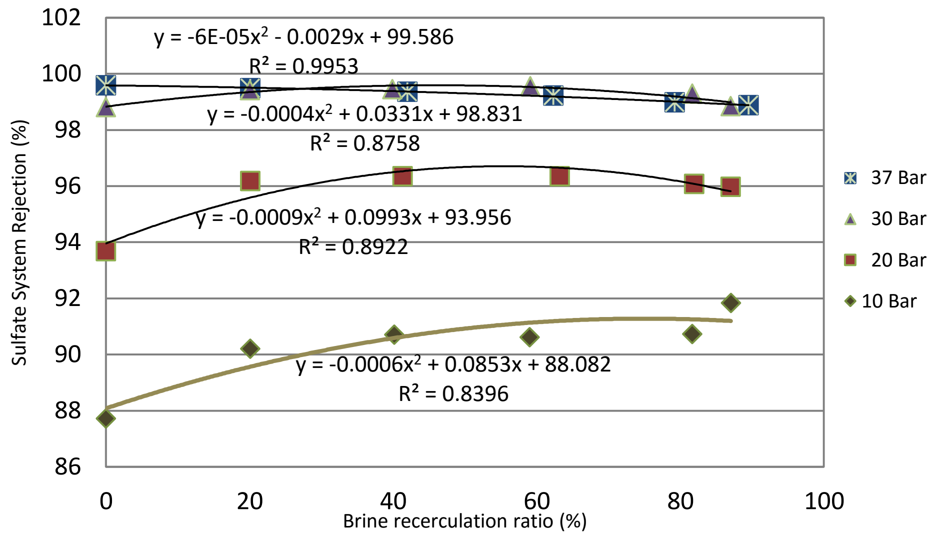
APPENDICES

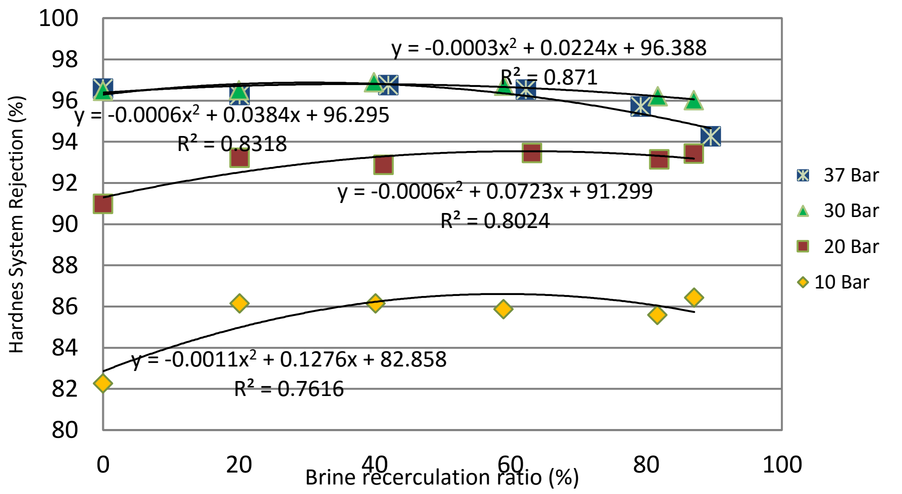
Appendix (1)

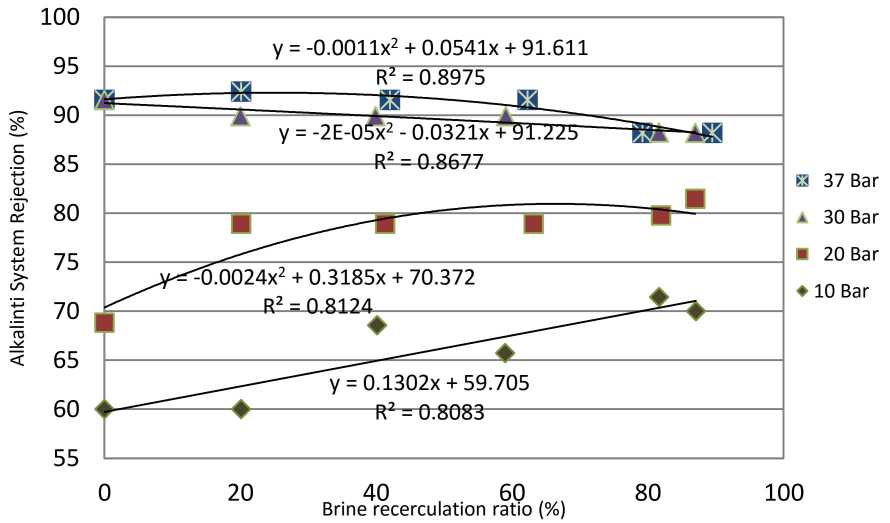
Second package of experiments: Effect of brine recirculation ration in seawater desalination using NF90 membrane

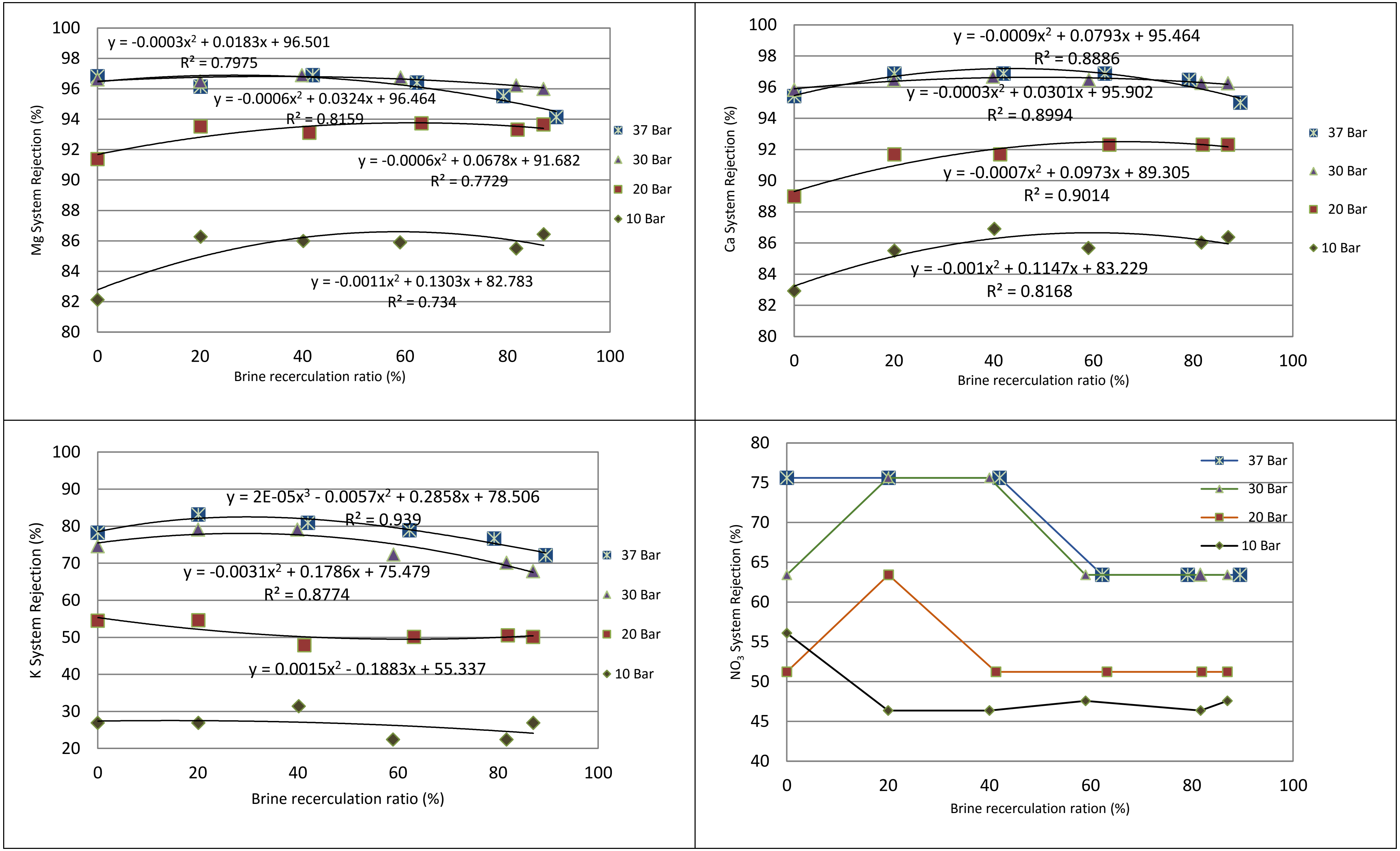
Test		Q_p	Q_B	Recovery rate	pH	E.C	TDS	Nitrate	Chloride	Sulfate	Alkalinity	Hardness	Calcium	Magnesium	Potassium	Sodium	Cadmium	Lead
Unit		L/h	L/h	%		Micro mho/cm	mg/l	mg/l as NO_3	mg/l as CL	mg/l as SO_4	mg/l as CO3	mg/l as $CaCO_3$	mg/l as Ca	mg/l as Mg	mg/l as K	mg/l as Na	µg/L as Cd	µg/L as Pb
Saltwater					7.13	59000	36580	8.2	20799	2958	119	7184	481	1452	445	12800	116	210
10 bar pressure with brine recirculation ratio	0%	4.8	926.8	0.5	7.71	38700	23994	3.6	12766	363	47	1274	82	259	325	8800	97	181
	20%	4.1	755.4	0.5	8.03	39200	24304	4.4	13842	290	41	995	70	199	325	9000	56	156
	40%	4.7	566.4	0.8	6.71	38600	23932	4.4	13483	275	37	995	63	203	305	8800	97	170
	60%	4.4	394.8	1.1	7.61	39500	24490	4.3	13627	278	41	1015	69	205	345	9200	101	165
	80%	4.6	177.1	2.5	7.68	39300	24366	4.4	13627	274	34	1035	67	210	345	9000	60	195
	90%	5.1	128.2	3.9	7.65	38700	23994	4.3	13412	280	36	975	66	197	325	8800	65	80
20 bar pressure with brine recirculation ratio	0%	17.09	941.34	1.78	7.13	25900	16058	4	8548	187	37	647	53	125	202	5400	35	70
	20%	16.43	766.50	2.10	7.06	25600	15872	3	8463	113	25	486	40	94	202	5650	50	50
	40%	16.10	564.87	2.77	8.21	26600	16492	4	8822	108	25	511	40	100	232	6400	49	60
	60%	17.26	357.20	4.61	7.95	26400	16368	4	8822	108	25	470	37	91	222	6300	39	55
	80%	16.14	174.88	8.45	7.8	27700	17174	4	9324	116	24	492	37	97	220	6320	44	90
	90%	16.49	140.13	10.53	7.5	27600	17112	4	9324	119	22	472	37	92	222	6100	50	60
30 bar pressure with brine recirculation ratio	0%	47.10	882.72	5.07	6.02	12960	8035	3	4231	35	10	253	20	49	113	2600	19	69
	20%	43.38	706.24	5.79	6.46	12910	8004	2	4303	17	12	251	17	51	93	2600	31	56
	40%	45.63	525.31	7.99	6.42	13560	8407	2	4303	16	12	223	16	45	93	2500	29	55
	60%	43.54	337.94	11.41	6.55	14990	9294	3	5020	13	12	235	17	47	123	3000	34	50
	80%	40.33	182.22	18.12	6.46	17004	10542	3	5738	21	14	273	18	55	133	3400	42	48
	90%	38.57	137.16	21.95	6.59	18001	11161	3	6024	34	14	285	18	58	143	3800	40	45
37 bar pressure with brine recirculation ratio	0%	72.11	853.20	7.79	7.58	9540	5915	2	3079	12	10	245	22	46	97	2000	29	39
	20%	69.01	698.30	8.99	6.65	9210	5710	2	3079	15	9	267	15	56	75	1900	25	40
	40%	64.55	521.30	11.02	6.56	9930	6157	2	3260	19	10	233	15	45	85	2000	20	42
	60%	60.00	340.00	15.00	6.49	10940	6783	3	3659	23	10	249	15	52	94	2200	30	39
	80%	53.37	192.30	21.72	6.4	13250	8215	3	4492	30	14	308	17	65	104	2800	32	40
	90%	39.52	80.02	33.06	6.34	15280	9474	3	5216	33	14	412	24	85	124	3600	25	43

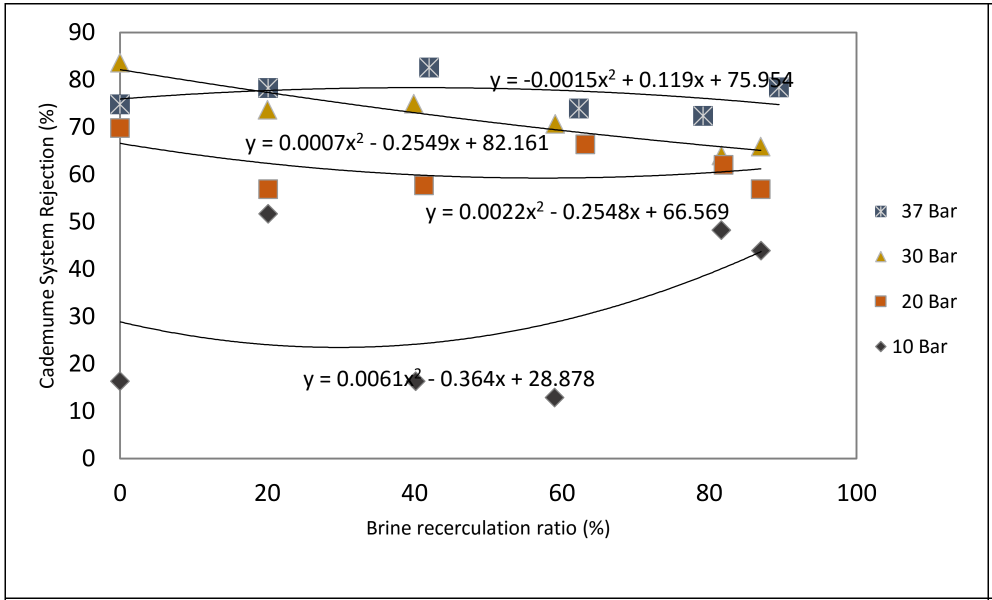

Na System Rejection (%)
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
Brine recercuлation ratio(%)
y = -0.0032x² + 0.1687x + 83.807
R² = 0.9598
y = -0.0021x² + 0.0887x + 79.463
R² = 0.9616
y = 0.0021x² - 0.2586x + 58.485
y = -0.0073x + 30.56
37 Bar
30 Bar
20 Bar
10 Bar

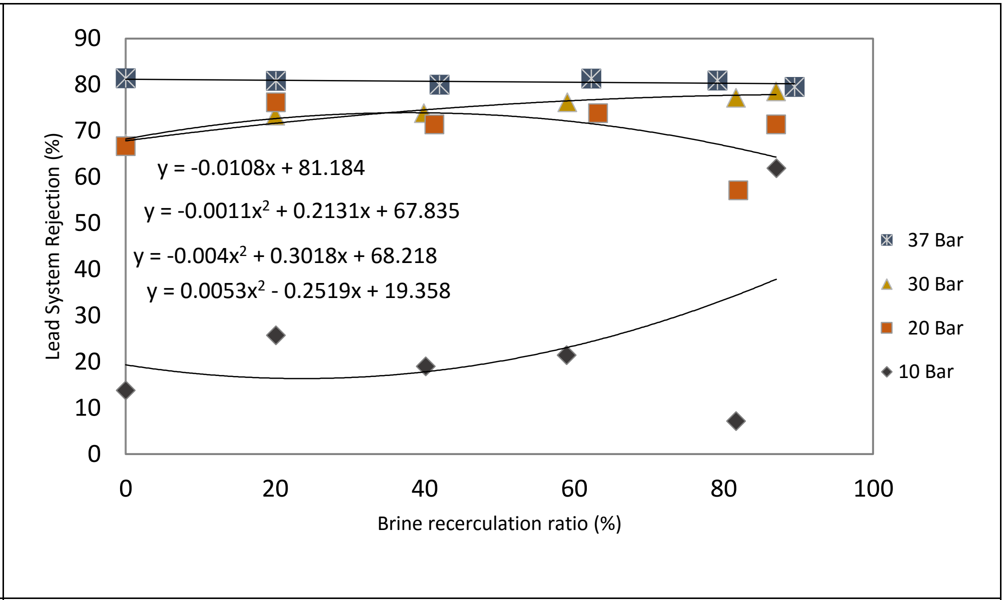

Sulfate System Rejection (%)
102
100
98
96
94
92
90
88
86
0
20
40
60
80
100
Brine recerculation ratio (%)
y = -6E-05x² - 0.0029x + 99.586
R² = 0.9953
y = -0.0004x² + 0.0331x + 98.831
R² = 0.8758
y = -0.0009x² + 0.0993x + 93.956
R² = 0.8922
y = -0.0006x² + 0.0853x + 88.082
R² = 0.8396
37 Bar
30 Bar
20 Bar
10 Bar

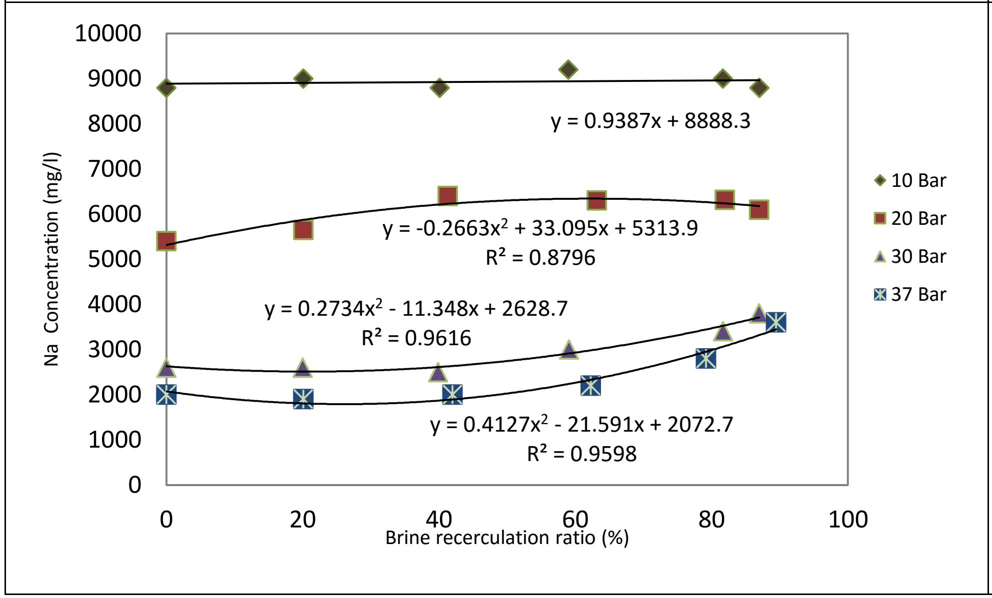

Hardnes System Rejection (%)
100
98
96
94
92
90
88
86
84
82
80
0
20
40
60
80
100
Brine recerculation ratio (%)
y = -0.0003x² + 0.0224x + 96.388
R² = 0.871
y = -0.0006x² + 0.0384x + 96.295
R² = 0.8318
y = -0.0006x² + 0.0723x + 91.299
R² = 0.8024
y = -0.0011x² + 0.1276x + 82.858
R² = 0.7616
37 Bar
30 Bar
20 Bar
10 Bar

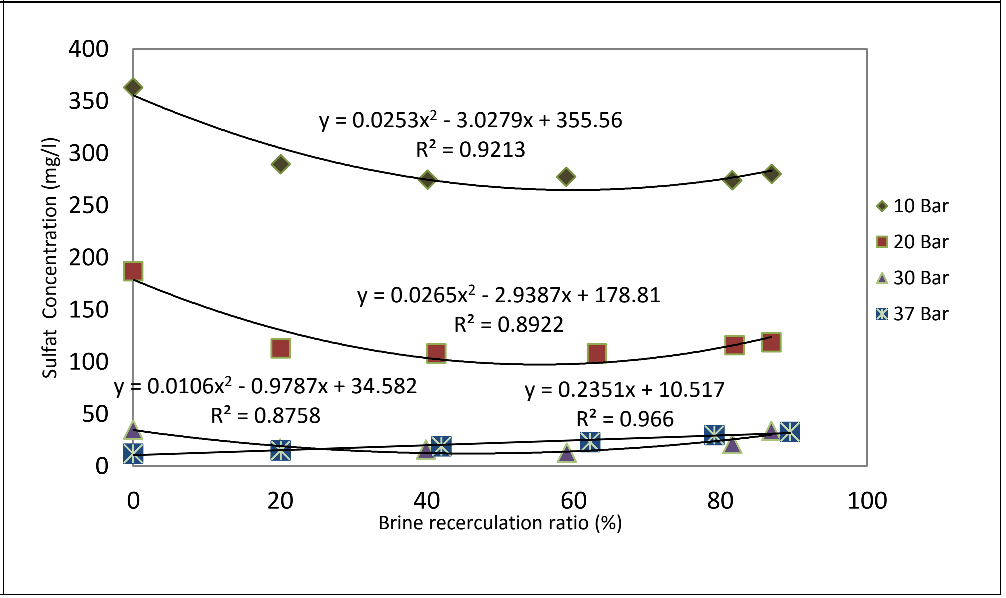

Alkalinti System Rejection (%)
100
95
90
85
80
75
70
65
60
55
0
20
40
60
80
100
Brine recerculation ratio (%)
y = -0.0011x² + 0.0541x + 91.611
R² = 0.8975
y = -2E-05x² - 0.0321x + 91.225
R² = 0.8677
y = -0.0024x² + 0.3185x + 70.372
R² = 0.8124
y = 0.1302x + 59.705
R² = 0.8083
37 Bar
30 Bar
20 Bar
10 Bar

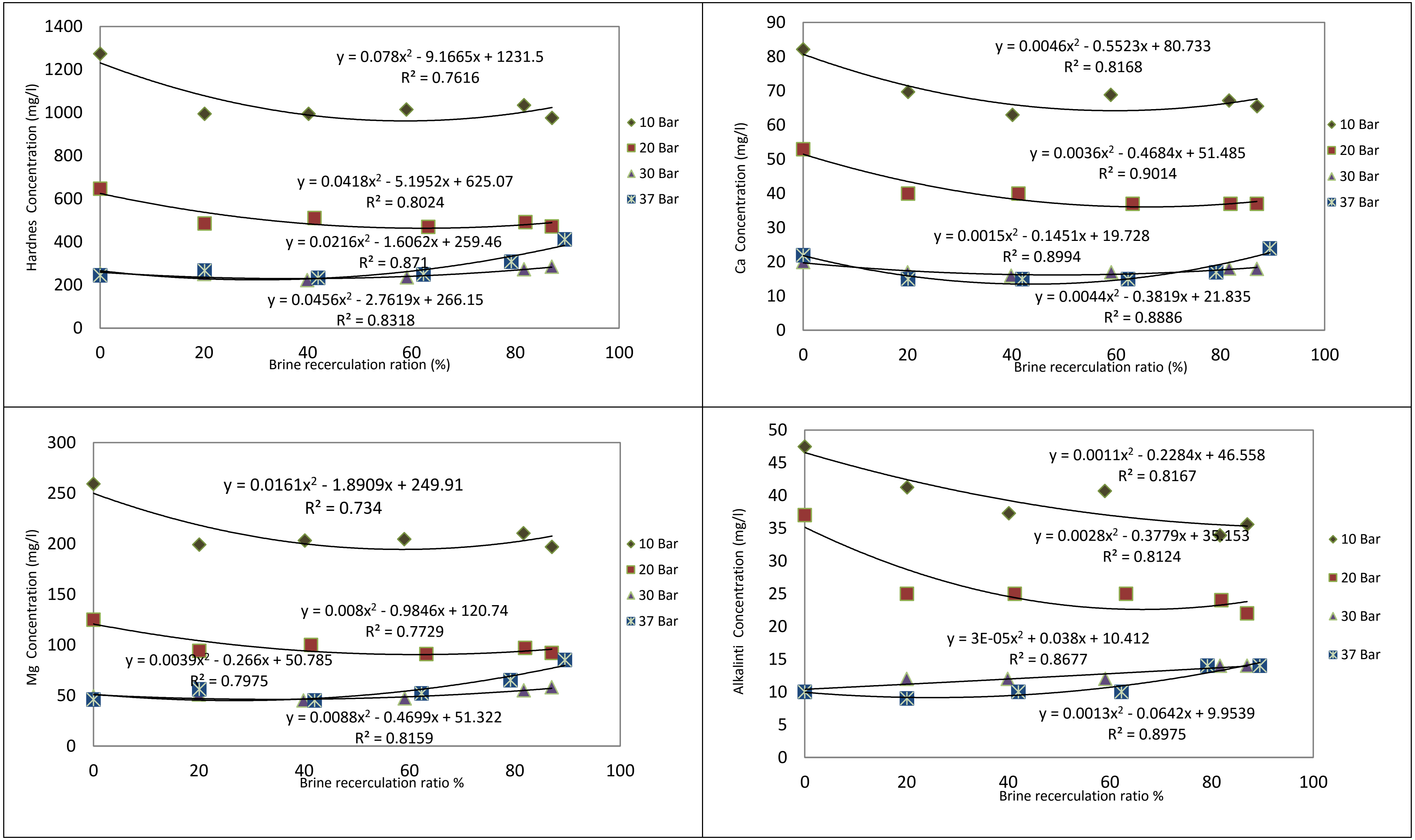

Mg System Rejection (%)
100
98
96
94
92
90
88
86
84
82
80
0
20
40
60
80
100
Brine rercerculation ratio (%)
y = -0.0003x² + 0.0183x + 96.501
R² = 0.7975
y = -0.0006x² + 0.0324x + 96.464
R² = 0.8159
y = -0.0006x² + 0.0678x + 91.682
R² = 0.7729
y = -0.0011x² + 0.1303x + 82.783
R² = 0.734
37 Bar
30 Bar
20 Bar
10 Bar
Ca System Rejection (%)
y = -0.0009x² + 0.0793x + 95.464
R² = 0.8886
y = -0.0003x² + 0.0301x + 95.902
R² = 0.8994
y = -0.0007x² + 0.0973x + 89.305
R² = 0.9014
y = -0.001x² + 0.1147x + 83.229
R² = 0.8168
K System Rejection (%)
y = 2E-05x³ - 0.0057x² + 0.2858x + 78.506
R² = 0.939
y = -0.0031x² + 0.1786x + 75.479
R² = 0.8774
y = 0.0015x² - 0.1883x + 55.337
NO3 System Rejection (%)
80
75
70
65
60
55
50
45
40
Brine rercerculation ration (%)

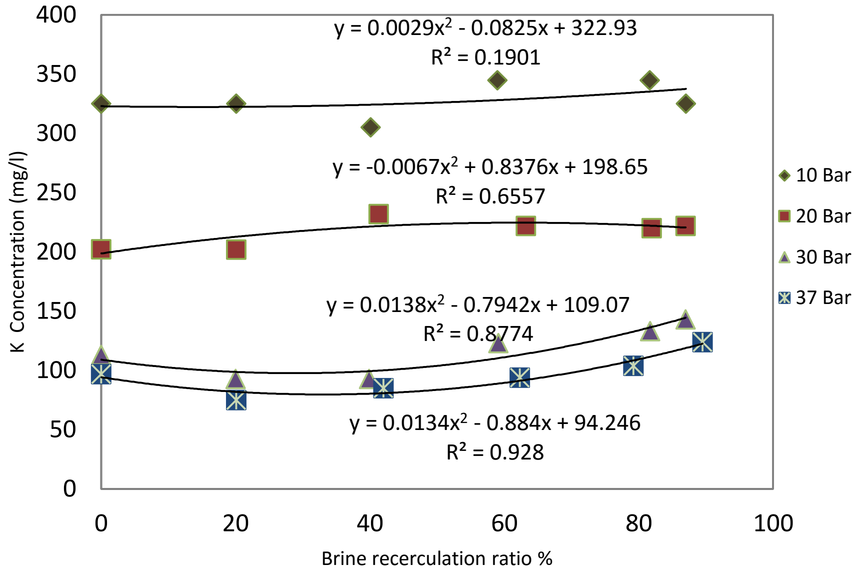

Cademume System Rejection (%)
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
Brine rercerculation ratio (%)
y = -0.0015x² + 0.119x + 75.954
y = 0.0007x² - 0.2549x + 82.161
y = 0.0022x² - 0.2548x + 66.569
y = 0.0061x² - 0.364x + 28.878
37 Bar
30 Bar
20 Bar
10 Bar


Lead System Rejection (%)
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
Brine rercerculation ratio (%)
y = -0.0108x + 81.184
y = -0.0011x² + 0.2131x + 67.835
y = -0.004x² + 0.3018x + 68.218
y = 0.0053x² - 0.2519x + 19.358
37 Bar
30 Bar
20 Bar
10 Bar


Na Concentration (mg/l)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
20
40
60
80
100
Brine rercerculation ratio (%)
y = 0.9387x + 8888.3
y = -0.2663x² + 33.095x + 5313.9
R² = 0.8796
y = 0.2734x² - 11.348x + 2628.7
R² = 0.9616
y = 0.4127x² - 21.591x + 2072.7
R² = 0.9598
10 Bar
20 Bar
30 Bar
37 Bar


Sulfat Concentration (mg/l)
400
350
300
250
200
150
100
50
0
0
20
40
60
80
100
Brine rercerculation ratio (%)
y = 0.0253x² - 3.0279x + 355.56
R² = 0.9213
y = 0.0265x² - 2.9387x + 178.81
R² = 0.8922
y = 0.0106x² - 0.9787x + 34.582
R² = 0.8758
y = 0.2351x + 10.517
R² = 0.966
10 Bar
20 Bar
30 Bar
37 Bar

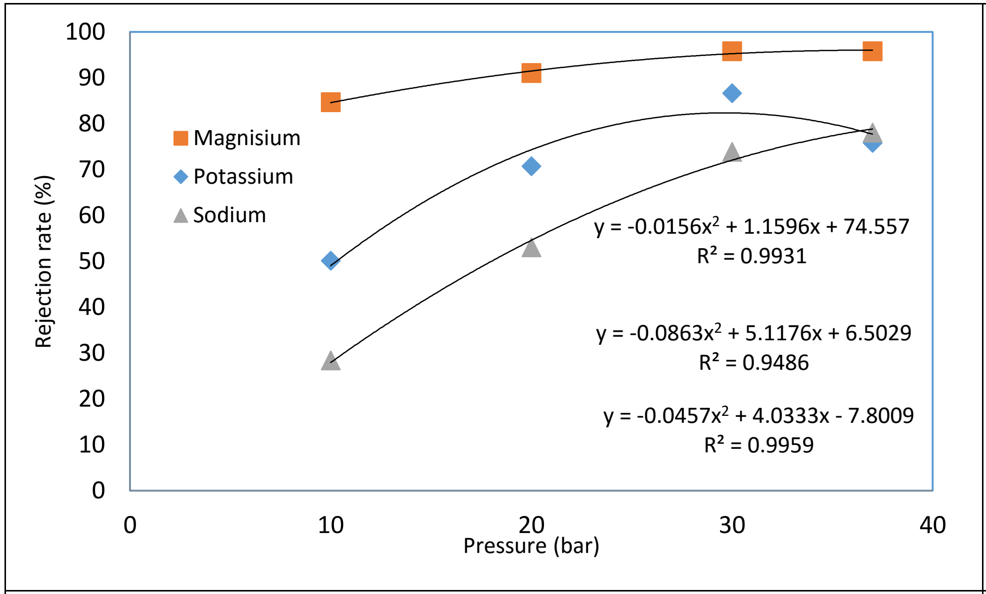

Hardnes Concentration (mg/l)
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
Brine recerculation ration (%)
y = 0.078x² - 9.1665x + 1231.5
R² = 0.7616
y = 0.0418x² - 5.1952x + 625.07
R² = 0.8024
y = 0.0216x² - 1.6062x + 259.46
R² = 0.871
y = 0.0456x² - 2.7619x + 266.15
R² = 0.8318
◆ 10 Bar
■ 20 Bar
▲ 30 Bar
⊠ 37 Bar
Ca Concentration (mg/l)
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
Brine recerculation ratio (%)
y = 0.0046x² - 0.5523x + 80.733
R² = 0.8168
y = 0.0036x² - 0.4684x + 51.485
R² = 0.9014
y = 0.0015x² - 0.1451x + 19.728
R² = 0.8994
y = 0.0044x² - 0.3819x + 21.835
R² = 0.8886
◆ 10 Bar
■ 20 Bar
▲ 30 Bar
⊠ 37 Bar
Mg Concentration (mg/l)
300
250
200
150
100
50
0
0
20
40
60
80
100
Brine recerculation ratio %
y = 0.0161x² - 1.8909x + 249.91
R² = 0.734
y = 0.008x² - 0.9846x + 120.74
R² = 0.7729
y = 0.0039x² - 0.266x + 50.785
R² = 0.7975
y = 0.0088x² - 0.4699x + 51.322
R² = 0.8159
◆ 10 Bar
■ 20 Bar
▲ 30 Bar
⊠ 37 Bar
Alkalinti Concentration (mg/l)
50
45
40
35
30
25
20
15
10
5
0
0
20
40
60
80
100
Brine recerculation ratio %
y = 0.0011x² - 0.2284x + 46.558
R² = 0.8167
y = 0.0028x² - 0.3779x + 35.153
R² = 0.8124
y = 3E-05x² + 0.038x + 10.412
R² = 0.8677
y = 0.0013x² - 0.0642x + 9.9539
R² = 0.8975
◆ 10 Bar
■ 20 Bar
▲ 30 Bar
⊠ 37 Bar

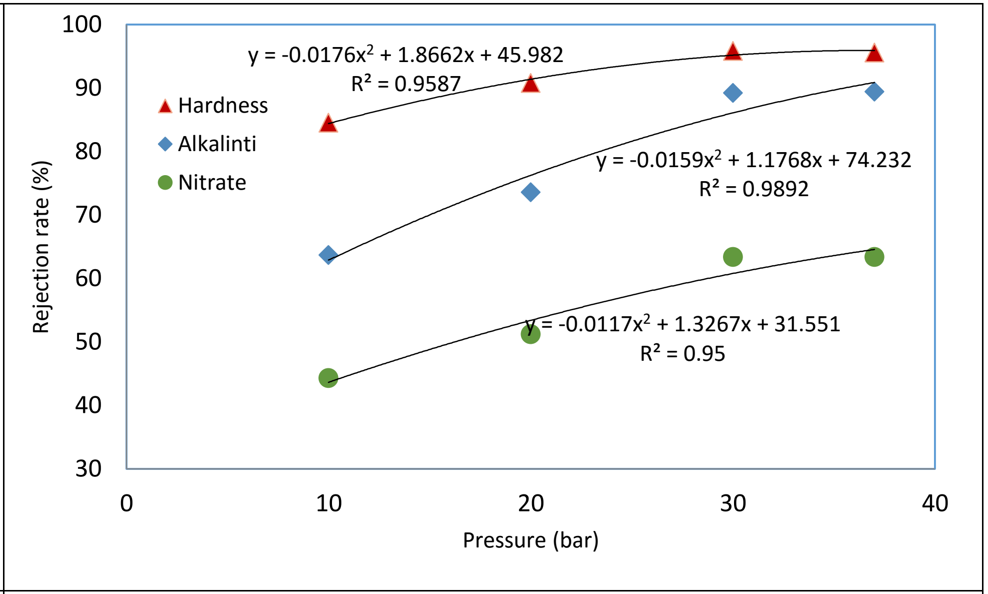

400
350
300
250
200
150
100
50
0
K Concentration (mg/l)
0
20
40
60
80
100
Brine recerculation ratio %
y = 0.0029x² - 0.0825x + 322.93
R² = 0.1901
y = -0.0067x² + 0.8376x + 198.65
R² = 0.6557
y = 0.0138x² - 0.7942x + 109.07
R² = 0.8774
y = 0.0134x² - 0.884x + 94.246
R² = 0.928
◆ 10 Bar
■ 20 Bar
▲ 30 Bar
☒ 37 Bar

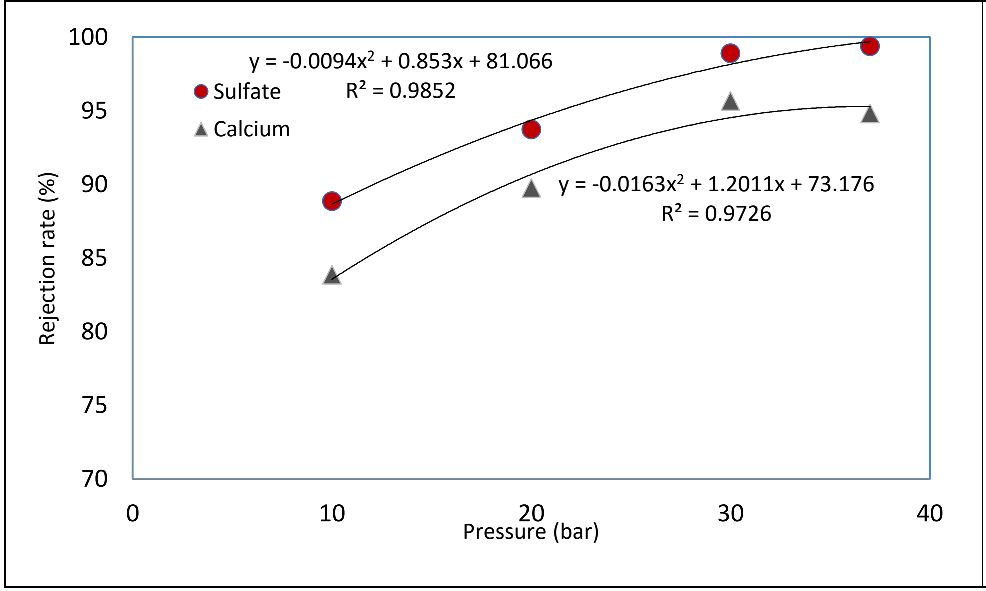
Appendix (2)

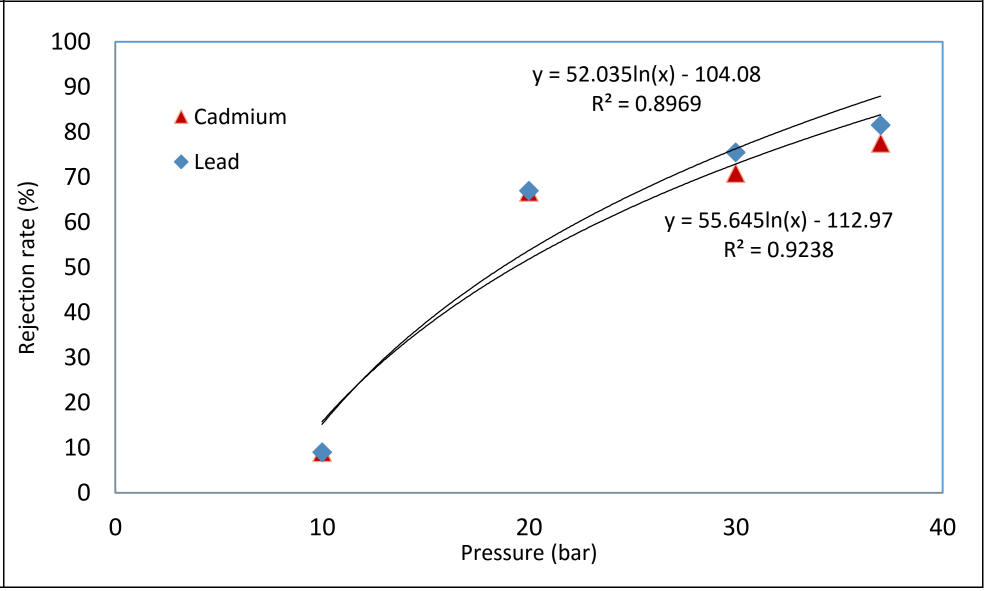
Third package of experiments: Seawater desalination using NF90 Membrane

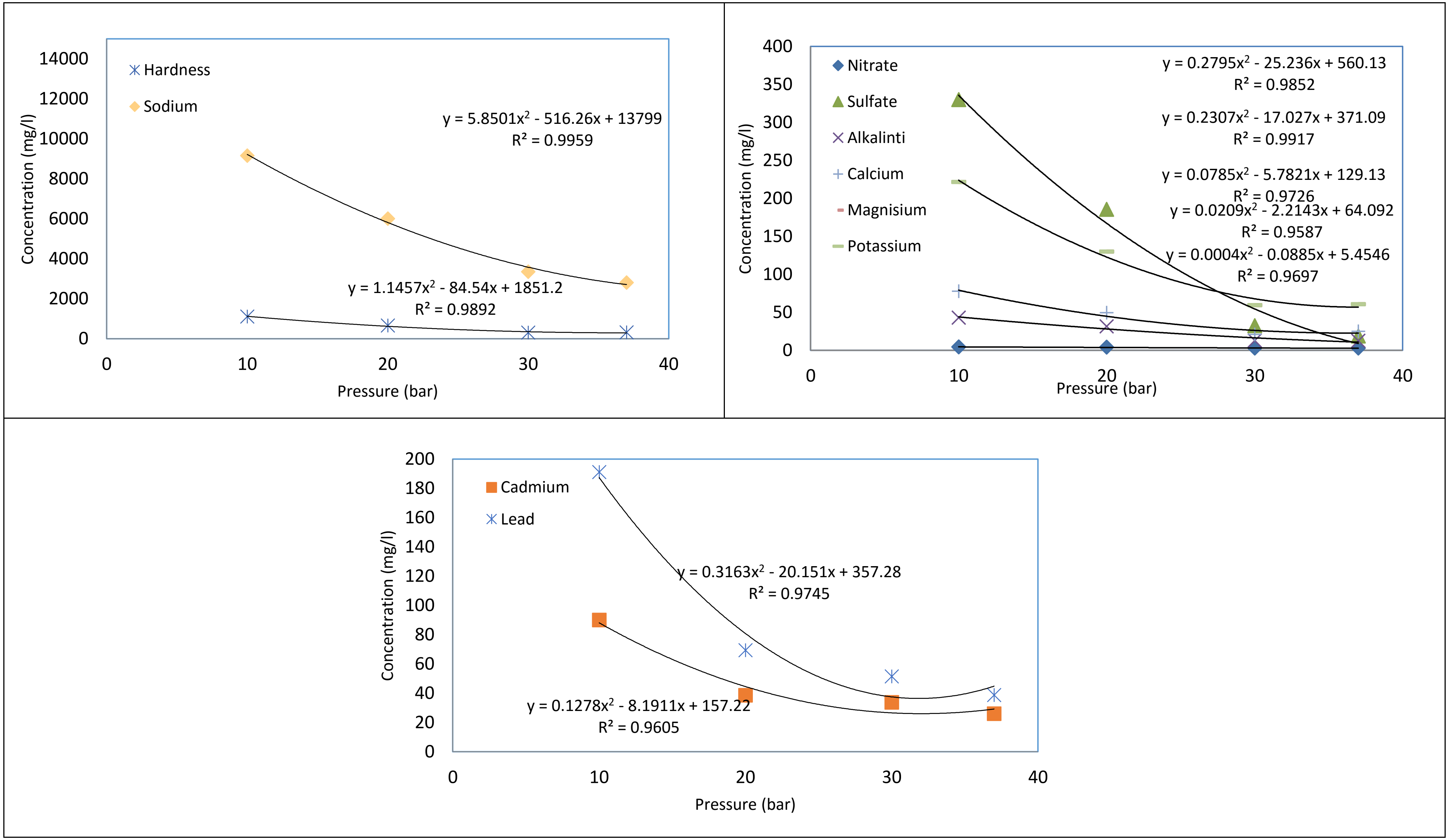
Test		Q_p	Q_B	Recovery rate	pH	E.C	TDS	Nitrate	Chloride	Sulfate	Alkalinity	Hardness	Calcium	Magnesium	Potassium	Sodium	Cadmium	Lead
Unit		L/h	L/h	%		Micro mho/cm	mg/l	mg/l as NO_3	mg/l as CL	mg/l as SO_4	mg/l as CO_3	mg/l as $CaCO_3$	mg/l as Ca	mg/l as Mg	mg/l as K	mg/l as Na	µg/L as Cd	µg/L as Pb
Saltwater					7.13	59000	36580	8.2	20799	2958	119	7184	481	1452	445	12800	116	210
10 bar with membrane number	1	4.8	926.8	0.5	7.71	38700	23994	4	12766	363	47	1274	82	259	325	8800	97	181
	2	4.3	940.3	0.4	7.72	40300	24986	5	13985	303	41	995	81	192	345	9200	105	199
	3	4.5	936.3	0.5	7.88	40200	24924	5	14201	298	46	1075	84	210	305	9400	99	197
	4	4.2	949.5	0.4	7.95	41100	25482	5	13985	411	46	1214	83	244	325	9000	84	205
	5	4.2	965.5	0.4	7.96	40300	24986	5	13842	297	41	1015	70	204	345	9200	84	210
	6	4.2	935.4	0.4	7.91	41000	25420	5	14129	307	37	1055	66	216	345	9400	69	155
20 bar with membrane number	1	17.09	941.34	1.78	7.13	25900	16058	4	8548	187	37	647	53	125	202	5400	35	70
	2	17.08	924.90	1.81	7.22	27400	16988	4	8965	181	25	667	47	133	212	5650	32	75
	3	17.01	937.71	1.78	6.7	28300	17546	4	9682	184	28	661	52	129	22	6100	39	65
	4	16.53	904.37	1.79	7.15	28300	17546	4	9682	200	42	677	56	130	232	6200	42	70
	5	16.84	937.72	1.76	7.26	28200	17484	4	9324	177	27	647	42	131	222	6300	40	65
	6	16.50	921.50	1.76	7.04	29000	17980	4	9682	184	29	657	46	132	202	6400	44	71
30 bar with membrane number	1	47.1	882.7	5.07	6.02	12960	8035	3	4231	35	10	253	20	49	113	2600	19	69
	2	45.5	893.0	4.85	6	14120	8754	3	4662	25	10	299	23	58	113	2800	29	53
	3	46.1	873.9	5.01	6	16360	10143	3	5451	19	14	332	17	71	123	3300	31	46
	4	41.6	883.4	4.50	6.2	17660	10949	3	5989	40	14	293	21	58	143	3700	37	47
	5	40.4	873.4	4.43	6.3	18340	11371	3	5881	37	14	289	23	56	143	3600	42	43
	6	38.4	885.8	4.15	6.39	19550	12121	3	6670	41	15	318	22	64	153	4300	49	48
37 bar with membrane number	1	72.1	853.2	7.79	7.58	9540	5915	2	3079	12	10	245	22	46	97	2000	29	39
	2	67.4	900.2	6.97	7.52	10710	6640	2	3550	14	12	271	22	52	104	2350	25	30
	3	54.4	878.1	5.84	7.42	12860	7973	3	4311	18	12	295	22	58	124	2700	26	40
	4	49.3	878.1	5.32	7.18	14650	9083	4	4963	22	14	314	27	60	134	3200	26	40
	5	46.2	879.0	4.99	6.48	15610	9678	3	5361	24	14	416	30	83	45	3500	20	42
	6	36.3	909.4	3.84	6.62	17490	10844	4	5977	30	15	422	32	83	154	4000	29	45


100
90
80
70
60
50
40
30
20
10
0
Rejection rate (%)
Magnisium
Potassium
Sodium
y = -0.0156x² + 1.1596x + 74.557
R² = 0.9931
y = -0.0863x² + 5.1176x + 6.5029
R² = 0.9486
y = -0.0457x² + 4.0333x - 7.8009
R² = 0.9959
0
10
20
30
40
Pressure (bar)


100
90
80
70
60
50
40
30
Rejection rate (%)
y = -0.0176x² + 1.8662x + 45.982
R² = 0.9587
Hardness
Alkalinti
Nitrate
y = -0.0159x² + 1.1768x + 74.232
R² = 0.9892
y = -0.0117x² + 1.3267x + 31.551
R² = 0.95
0
10
20
30
40
Pressure (bar)


100
95
90
85
80
75
70
Rejection rate (%)
y = -0.0094x² + 0.853x + 81.066
R² = 0.9852
Sulfate
Calcium
y = -0.0163x² + 1.2011x + 73.176
R² = 0.9726
0
10
20
30
40
Pressure (bar)

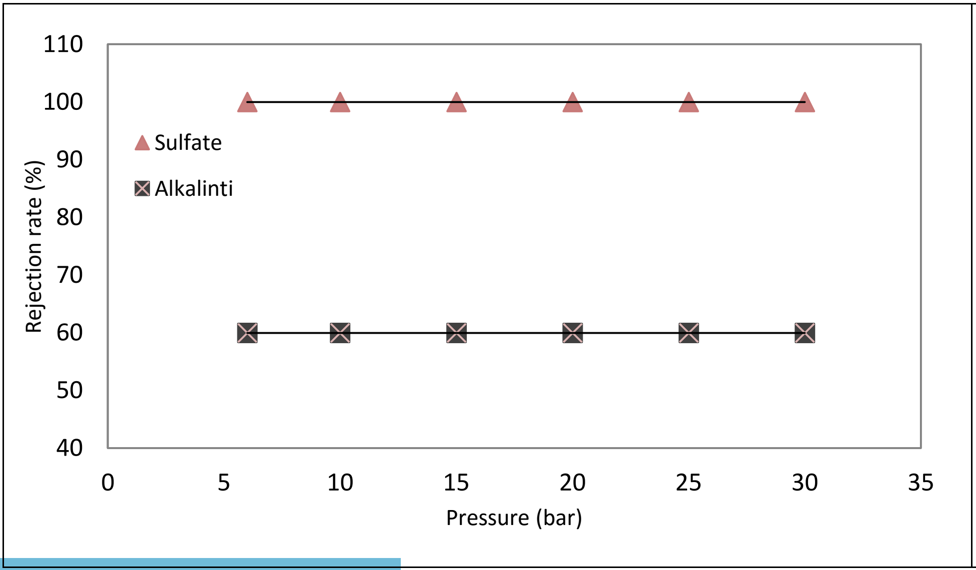

100
90
80
70
60
50
40
30
20
10
0
Rejection rate (%)
y = 52.035ln(x) - 104.08
R² = 0.8969
Cadmium
Lead
y = 55.645ln(x) - 112.97
R² = 0.9238
0
10
20
30
40
Pressure (bar)

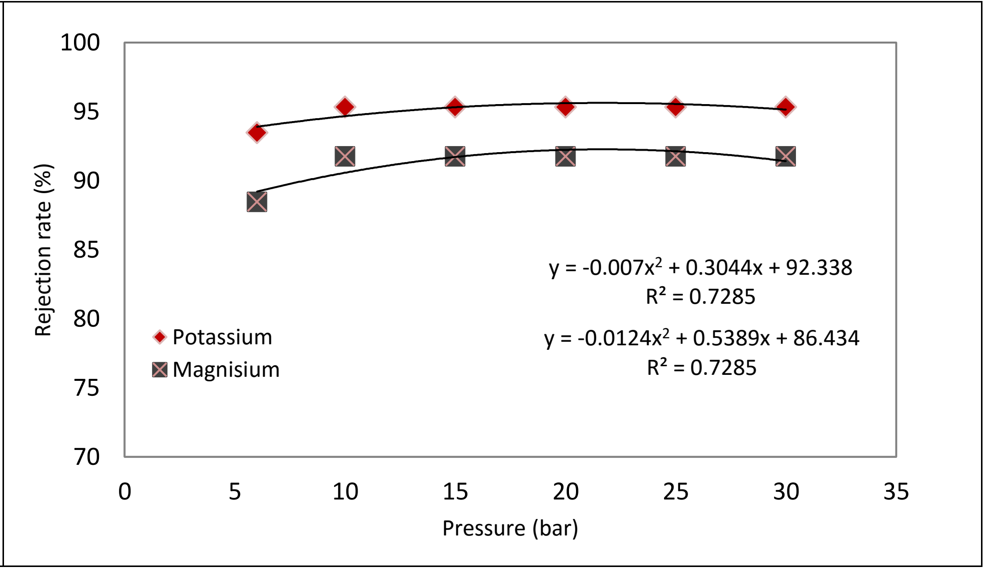

Concentration (mg/l)
14000
12000
10000
8000
6000
4000
2000
0
0
10
20
30
40
Pressure (bar)
Hardness
Sodium
y = 5.8501x² - 516.26x + 13799
R² = 0.9959
y = 1.1457x² - 84.54x + 1851.2
R² = 0.9892
Concentration (mg/l)
400
350
300
250
200
150
100
50
0
0
10
20
30
40
Pressure (bar)
Nitrate
Sulfate
Alkalinti
Calcium
Magnisium
Potassium
y = 0.2795x² - 25.236x + 560.13
R² = 0.9852
y = 0.2307x² - 17.027x + 371.09
R² = 0.9917
y = 0.0785x² - 5.7821x + 129.13
R² = 0.9726
y = 0.0209x² - 2.2143x + 64.092
R² = 0.9587
y = 0.0004x² - 0.0885x + 5.4546
R² = 0.9697
Concentration (mg/l)
200
180
160
140
120
100
80
60
40
20
0
0
10
20
30
40
Pressure (bar)
Cadmium
Lead
y = 0.3163x² - 20.151x + 357.28
R² = 0.9745
y = 0.1278x² - 8.1911x + 157.22
R² = 0.9605

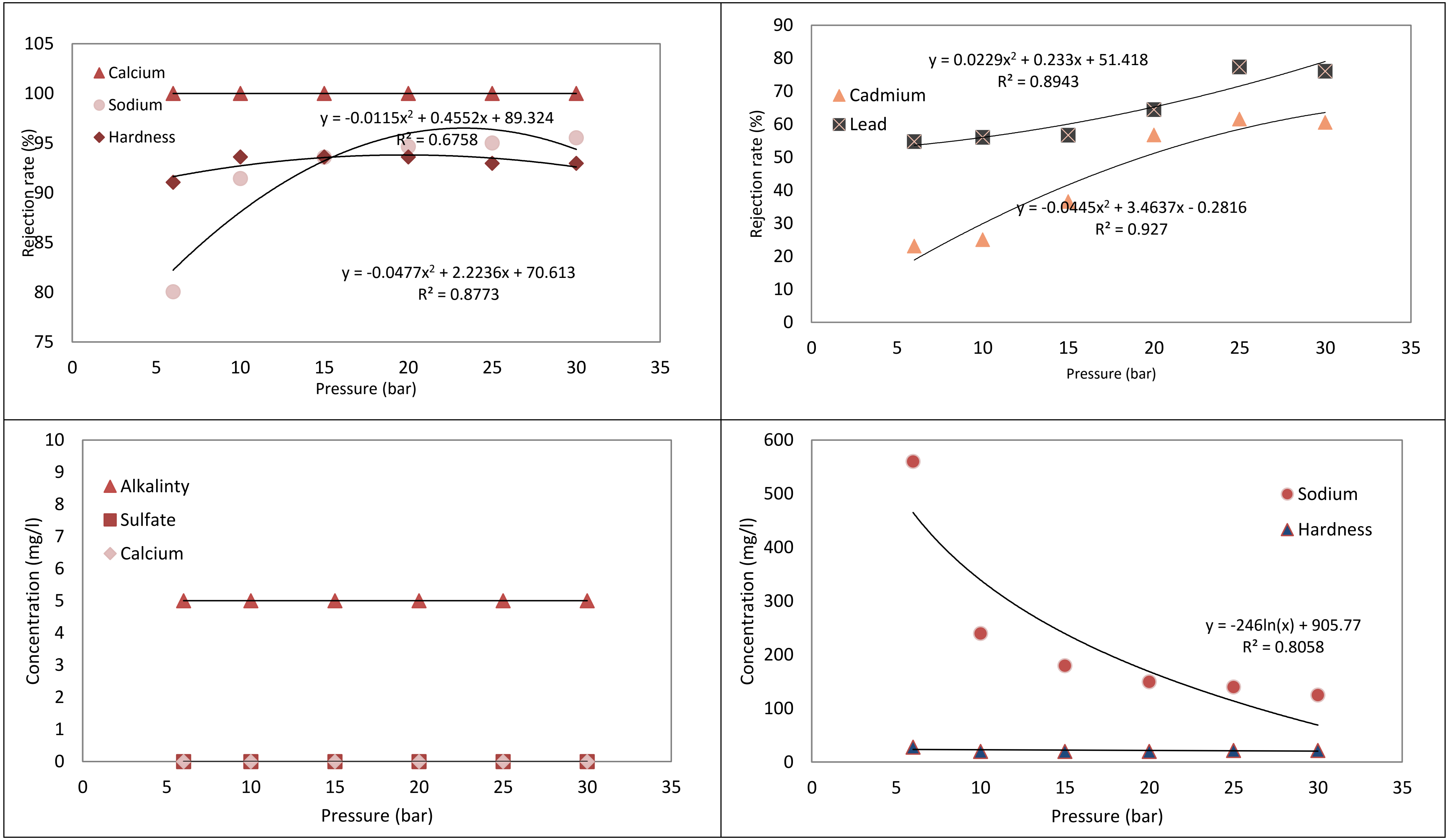
Appendix (3)

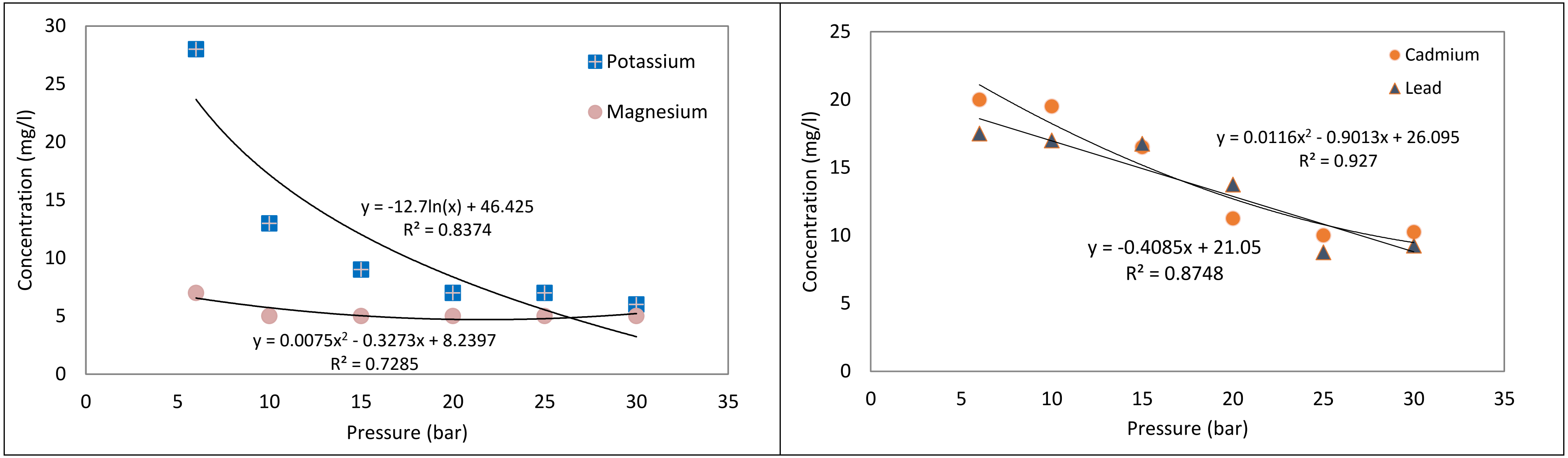
Forth package of experiments: Second pass desalination using NF90 membrane

Test		Qp	QB	Recovery rate	pH	E.C	TDS	Nitrate	Chloride	Sulfate	Alkalinity	Hardness	Calcium	Magnesium	Potassium	Sodium	Cadmium	Lead
Unit		L/h	L/h	%		Micro mho/cm	mg/l	mg/l as NO_3	mg/l as CL	mg/l as SO_4	mg/l as CO_3	mg/l as $CaCO_3$	mg/l as Ca	mg/l as Mg	mg/l as K	mg/l as Na	µg/L as Cd	µg/L as Pb
Collected permeate					7.21	12857	7972	3	4314	19	12	313	25	61	108	2807	26	39
Pressure(bar)	6	17.5	912.8	1.9	5.71	3350	2077	3	1087	0	5	28	0	7	28	560	20	18
	10	56.3	876.9	6.0	6.03	1452	900	2	456	0	5	20	0	5	13	240	20	17
	15	98.2	829.7	10.6	6.1	1022	634	2	319	0	5	20	0	5	9	180	17	17
	20	134.3	786.9	14.6	6.19	865	536	1	268	0	5	20	0	5	7	150	11	14
	25	161.0	748.9	17.7	6.19	823	510	0	254	0	5	22	0	5	7	140	10	9
	30	184.0	731.3	20.1	6.23	729	452	0	225	0	5	22	0	5	6	125	10	9





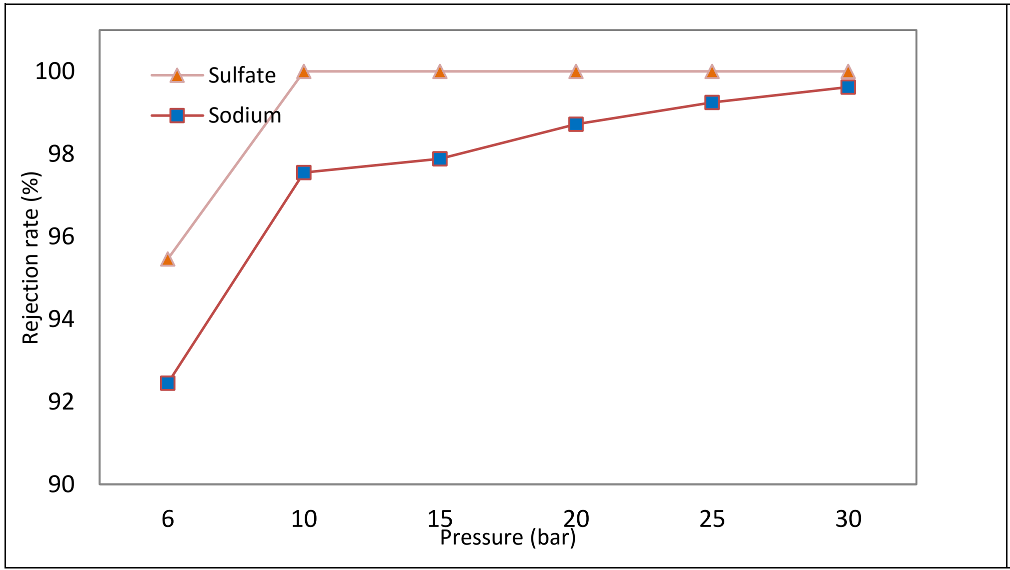

105
100
95
90
85
80
75
Rejection rate (%)
Calcium
Sodium
Hardness
y = -0.0115x² + 0.4552x + 89.324
R² = 0.6758
y = -0.0477x² + 2.2236x + 70.613
R² = 0.8773
0
5
10
15
20
25
30
35
Pressure (bar)
90
80
70
60
50
40
30
20
10
0
Rejection rate (%)
Cadmium
Lead
y = 0.0229x² + 0.233x + 51.418
R² = 0.8943
y = -0.0445x² + 3.4637x - 0.2816
R² = 0.927
0
5
10
15
20
25
30
35
Pressure (bar)
10
9
8
7
6
5
4
3
2
1
0
Concentration (mg/l)
Alkalinty
Sulfate
Calcium
0
5
10
15
20
25
30
35
Pressure (bar)
600
500
400
300
200
100
0
Concentration (mg/l)
Sodium
Hardness
y = -246ln(x) + 905.77
R² = 0.8058
0
5
10
15
20
25
30
35
Pressure (bar)

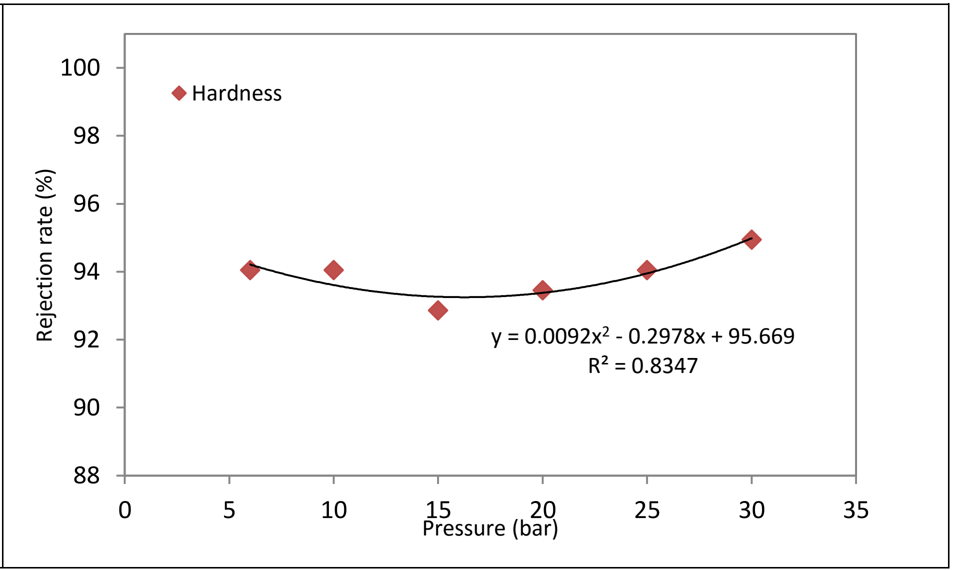

Concentration (mg/l)
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
Pressure (bar)
Potassium
Magnesium
y = -12.7ln(x) + 46.425
R² = 0.8374
y = 0.0075x² - 0.3273x + 8.2397
R² = 0.7285
Concentration (mg/l)
25
20
15
10
5
0
0
5
10
15
20
25
30
35
Pressure (bar)
Cadmium
Lead
y = 0.0116x² - 0.9013x + 26.095
R² = 0.927
y = -0.4085x + 21.05
R² = 0.8748

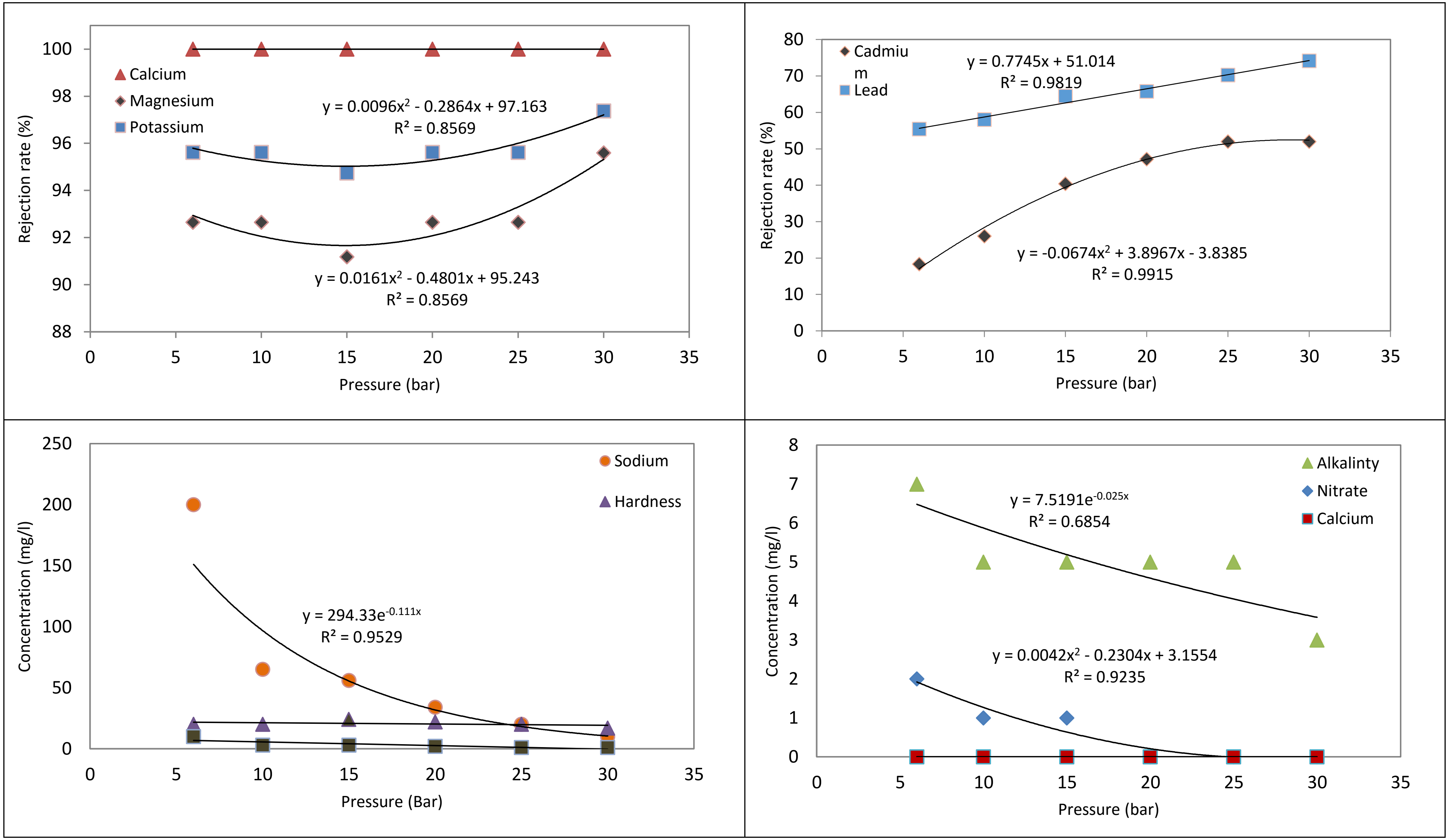
Appendix (4)

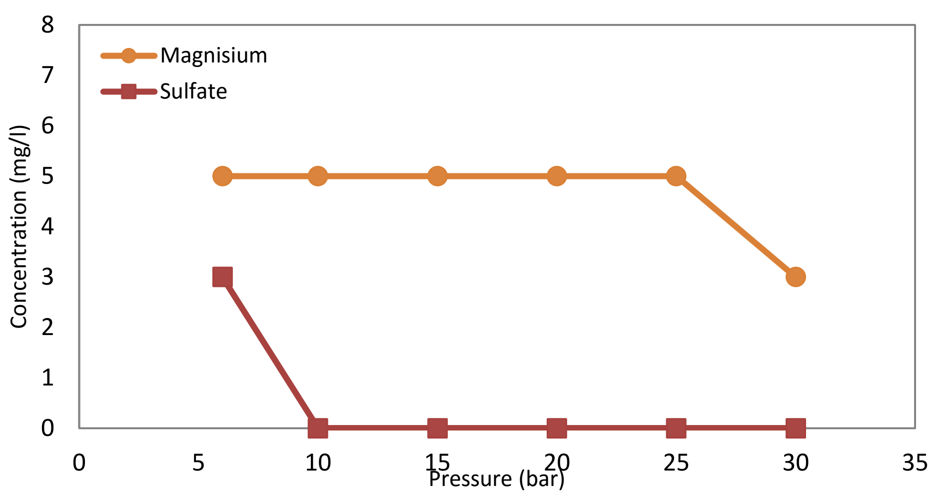
Fifth package of experiments: Second pass desalination using RO brackish water membrane

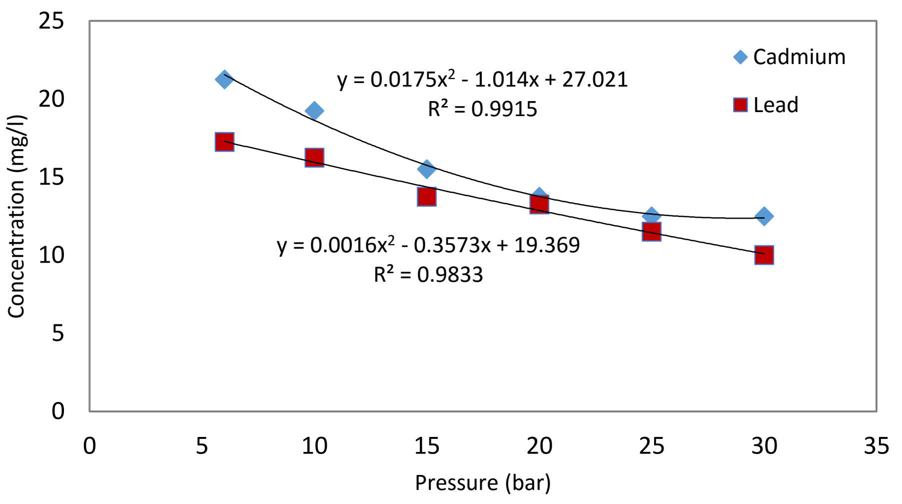
Test		Q_P	Q_B	Recovery rate	pH	E.C	TDS	Nitrate	Chloride	Sulfate	Alkalinity	Hardness	Calcium	Magnesium	Potassium	Sodium	Cadmium	Lead
Unit		L/h	L/h	%	0	Micro mho/cm	mg/l	mg/l as NO_3	mg/l as CL	mg/l as SO_4	mg/l as CO_3	mg/l as $CaCO_3$	mg/l as Ca	mg/l as Mg	mg/l as K	mg/l as Na	μg/L as Cd	μg/L as Pb
Collected permeate					7.21	12857	7972	3	4314	19	12	313	25	61	108	2807	26	39
Pressure(bar)	6	4.6	948.4	0.5	5.79	1190	738	2	362.00	3.00	7	20	0	5.00	10.00	200	21.25	17.25
	10	22.0	925.3	2.3	6.45	394	244	1	116.00	0.00	5	20	0	5.00	3.00	65	19.25	16.25
	15	51.1	886.8	5.4	6.31	334	207	1	101.00	0.00	5	24	0	5.00	3.00	56	15.50	13.75
	20	72.9	860.6	7.8	6.44	207	128	0	65.00	0.00	5	22	0	5.00	2.00	34	13.75	13.25
	25	100.0	828.5	10.8	6.6	124	77	0	29.00	0.00	5	20	0	5.00	1.00	20	12.50	11.5
	30	120.0	837.6	12.5	6.35	135	50	0	18.00	0.00	3	17	0	3.00	1.00	10	12.50	10






100
98
96
94
92
90
88
Rejection rate (%)
Calcium
Magnesium
Potassium
y = 0.0096x² - 0.2864x + 97.163
R² = 0.8569
y = 0.0161x² - 0.4801x + 95.243
R² = 0.8569
0
5
10
15
20
25
30
35
Pressure (bar)
80
70
60
50
40
30
20
10
0
Rejection rate (%)
Cadmiu
m
Lead
y = 0.7745x + 51.014
R² = 0.9819
y = -0.0674x² + 3.8967x - 3.8385
R² = 0.9915
0
5
10
15
20
25
30
35
Pressure (bar)
250
200
150
100
50
0
Concentration (mg/l)
Sodium
Hardness
y = 294.33e^-0.111x
R² = 0.9529
0
5
10
15
20
25
30
35
Pressure (Bar)
8
7
6
5
4
3
2
1
0
Concentration (mg/l)
Alkalinty
Nitrate
Calcium
y = 7.5191e^-0.025x
R² = 0.6854
y = 0.0042x² - 0.2304x + 3.1554
R² = 0.9235
0
5
10
15
20
25
30
35
Pressure (bar)

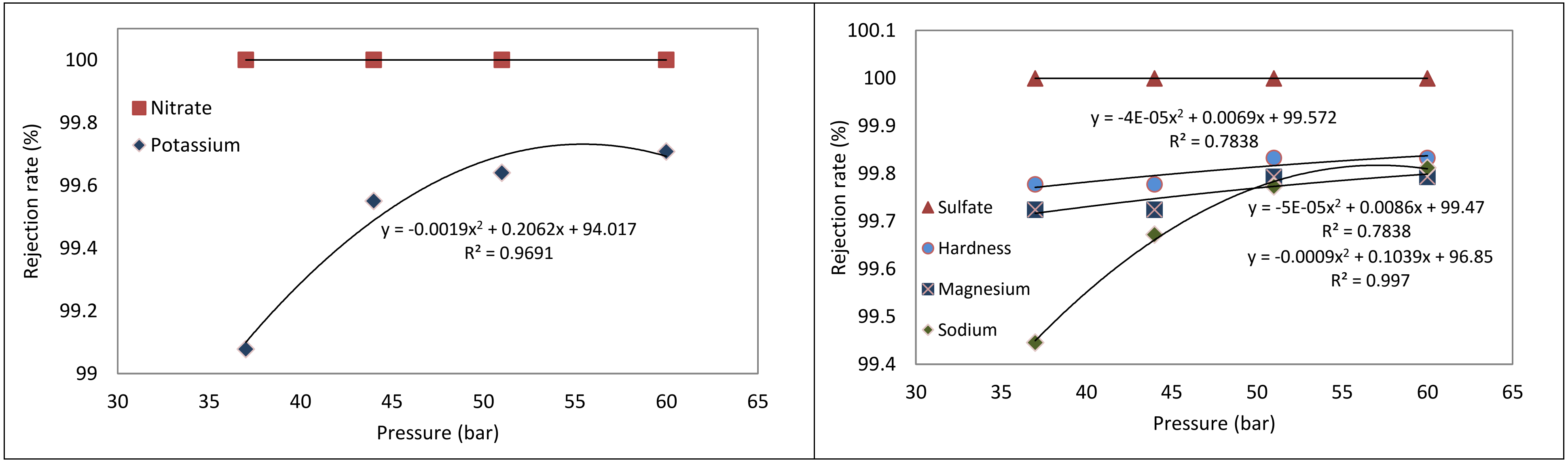

Magnisium
Sulfate
Concentration (mg/l)
8
7
6
5
4
3
2
1
0
0
5
10
15
20
25
30
35
Pressure (bar)

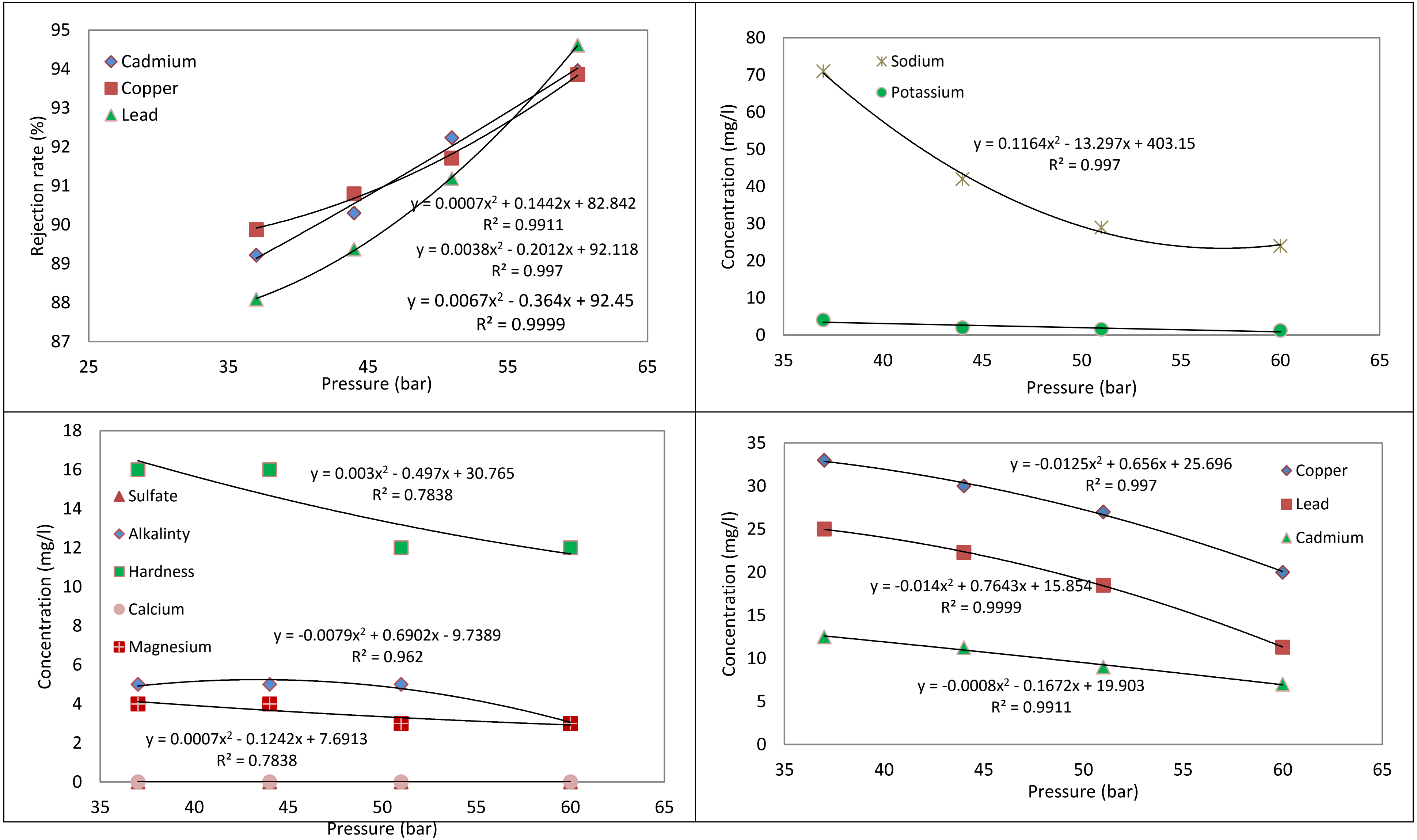

Cadmium
Lead
y = 0.0175x² - 1.014x + 27.021
R² = 0.9915
y = 0.0016x² - 0.3573x + 19.369
R² = 0.9833
Concentration (mg/l)
25
20
15
10
5
0
0
5
10
15
20
25
30
35
Pressure (bar)

Appendix (5)

Sixth package of experiments: Seawater desalination using RO seawater membrane

Test		Q_p	Q_B	Recovery rate	pH	E.C	TDS	Nitrate	Chloride	Sulfate	Alkalinity	Hardness	Calcium	Magnesium	Potassium	Sodium	Cadmium	Copper	Lead
Unit		L/h	L/h	%	0	Micro mho/cm	mg/l	mg/l as NO_3	mg/l as CL	mg/l as SO_4	mg/l as CO_3	mg/l as $CaCO_3$	mg/l as Ca	mg/l as Mg	mg/l as K	mg/l as Na	µg/L as Cd	µg/L as Cu	µg/L as Pb
Seawater					7.13	59000	36580	8	20799	2958	119	7184	481	1452	445	12800	116	326	210
Pressure(bar)	37	19.8	971.7	2.00	5.74	512	323	0	154	0	5	16	0	4	4	71	13	33	25
	44	38.4	936.4	3.94	5.56	292	181	0	86	0	5	12	0	3	2	42	11	30	22
	51	50.5	922.6	5.19	5.88	215	133	0	64	0	3	12	0	3	2	29	8	27	19
	60	71.4	905.6	7.31	5.07	175	108	0	52	0	3	10	0	2	1	24	7	20	11

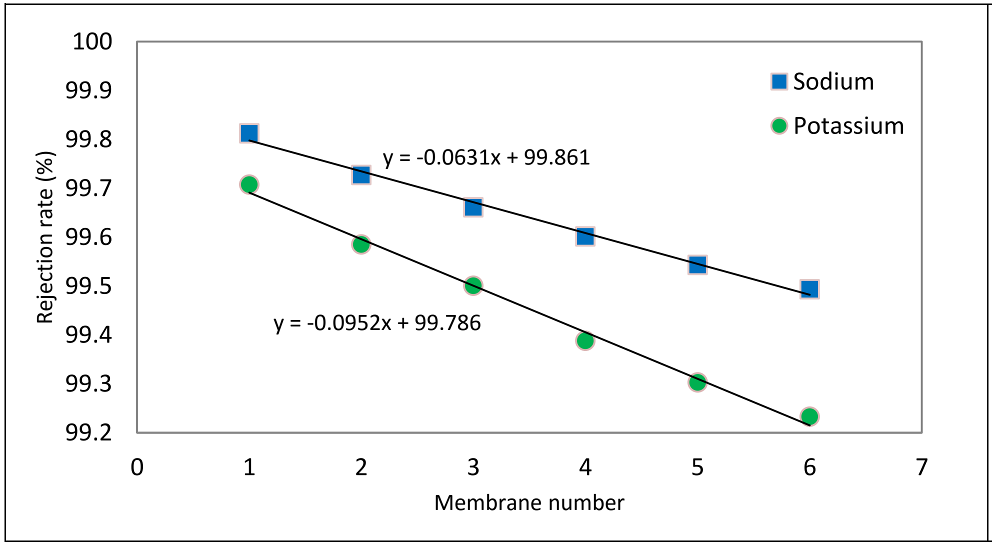


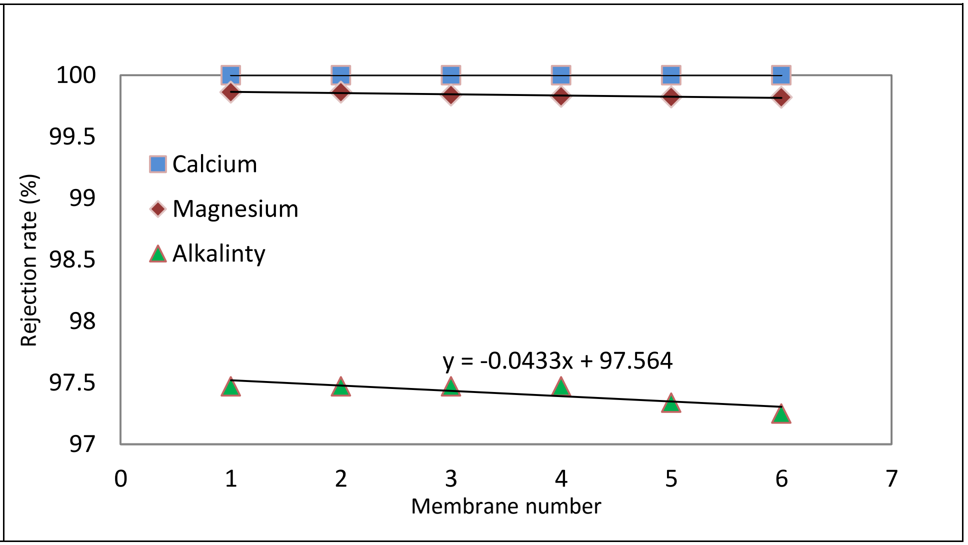

Rejection rate (%)
95
94
93
92
91
90
89
88
87
25
35
45
55
65
Pressure (bar)
◆ Cadmium
■ Copper
▲ Lead
y = 0.0007x² + 0.1442x + 82.842
R² = 0.9911
y = 0.0038x² - 0.2012x + 92.118
R² = 0.997
y = 0.0067x² - 0.364x + 92.45
R² = 0.9999
Concentration (mg/l)
80
70
60
50
40
30
20
10
0
35
40
45
50
55
60
65
Pressure (bar)
✳ Sodium
● Potassium
y = 0.1164x² - 13.297x + 403.15
R² = 0.997
Concentration (mg/l)
18
16
14
12
10
8
6
4
2
0
35
40
45
50
55
60
65
Pressure (bar)
▲ Sulfate
◆ Alkalinty
■ Hardness
● Calcium
⊞ Magnesium
y = 0.003x² - 0.497x + 30.765
R² = 0.7838
y = -0.0079x² + 0.6902x - 9.7389
R² = 0.962
y = 0.0007x² - 0.1242x + 7.6913
R² = 0.7838
Concentration (mg/l)
35
30
25
20
15
10
5
0
35
40
45
50
55
60
65
Pressure (bar)
◆ Copper
■ Lead
▲ Cadmium
y = -0.0125x² + 0.656x + 25.696
R² = 0.997
y = -0.014x² + 0.7643x + 15.854
R² = 0.9999
y = -0.0008x² - 0.1672x + 19.903
R² = 0.9911

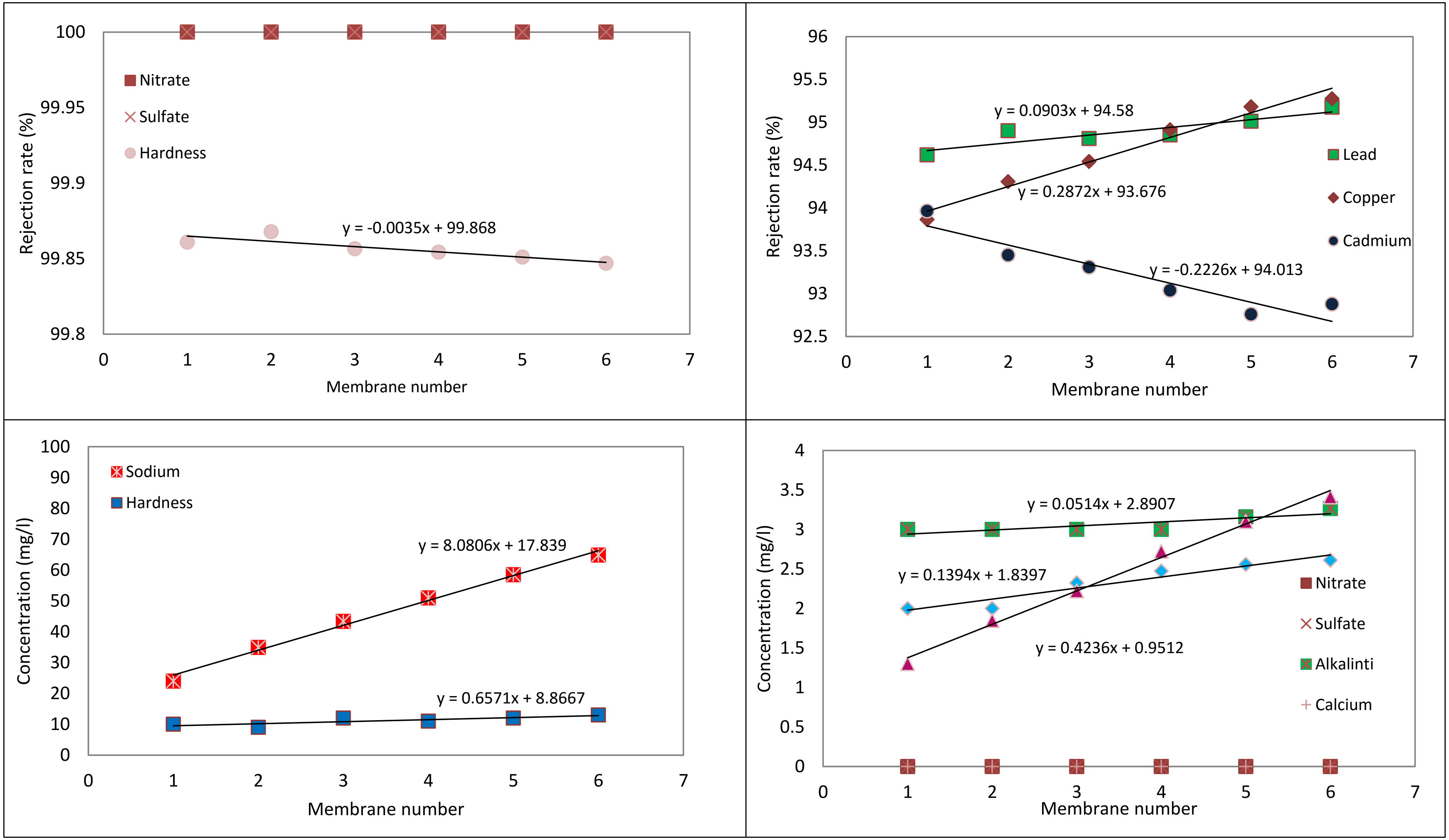
Appendix (6)

Seventh package of experiments: First pass desalination using RO seawater membrane at 60 bar pressure

Test		Q_p	Q_B	Recovery rate	pH	E.C	TDS	Nitrate	Chloride	Sulfate	Alkalinity	Hardness	Calcium	Magnesium	Potassium	Sodium	Cadmium	Copper	Lead
Unit		L/h	L/h	%	0	Micro mho/cm	mg/l	mg/l as NO_3	mg/l as CL	mg/l as SO_4	mg/l as CO_3	mg/l as $CaCO_3$	mg/l as Ca	mg/l as Mg	mg/l as K	mg/l as Na	µg/L as Cd	µg/L as Cu	µg/L as Pb
Seawater					7.13	59000	36580	8	20799	2958	119	7184	481	1452	445	12800	116	326	210
60 bar with membrane number	1	71.39	905.58	7.31	5.07	175	108	0	52	0	3	10	0	2	1	24	7	20	11
	2	67.92	864.22	7.29	5.23	296	184	0	86	0	3	9	0	2	2	46	8	17	10
	3	68.10	871.15	7.25	5.63	374	232	0	101	0	3	12	0	3	3	61	8	16	11
	4	59.25	878.05	6.32	5.82	467	290	0	132	0	3	11	0	3	5	78	9	12	11
	5	51.11	888.91	5.44	6.03	547	339	0	156	0	4	12	0	3	5	98	10	11	9
	6	45.48	890.48	4.86	6.12	596	370	0	170	0	4	13	0	3	6	110	7	13	8



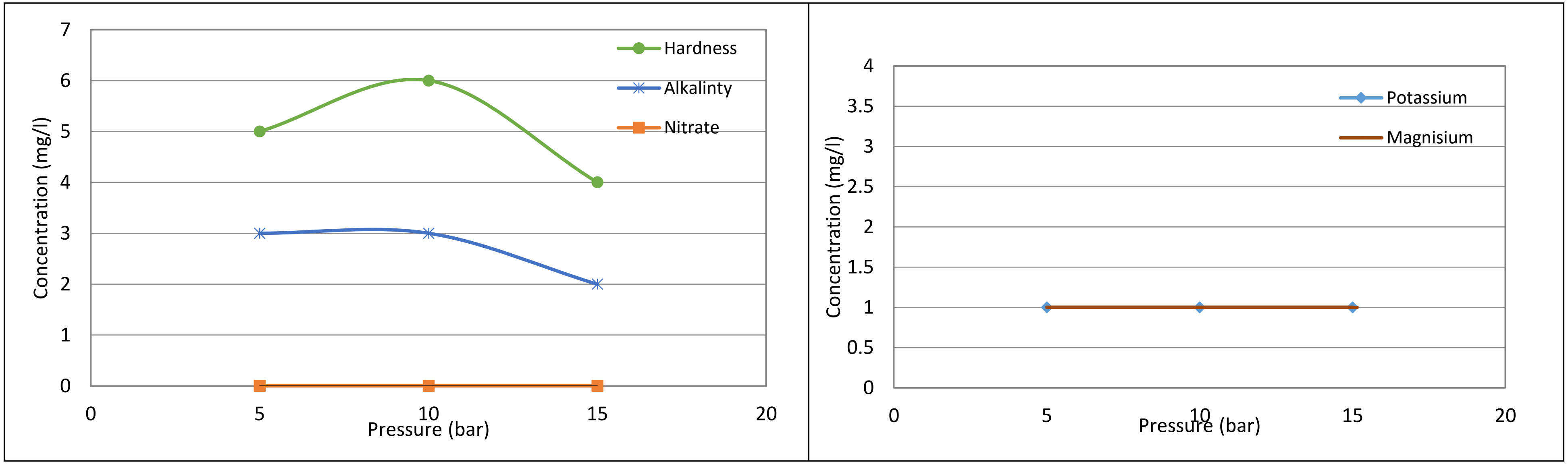


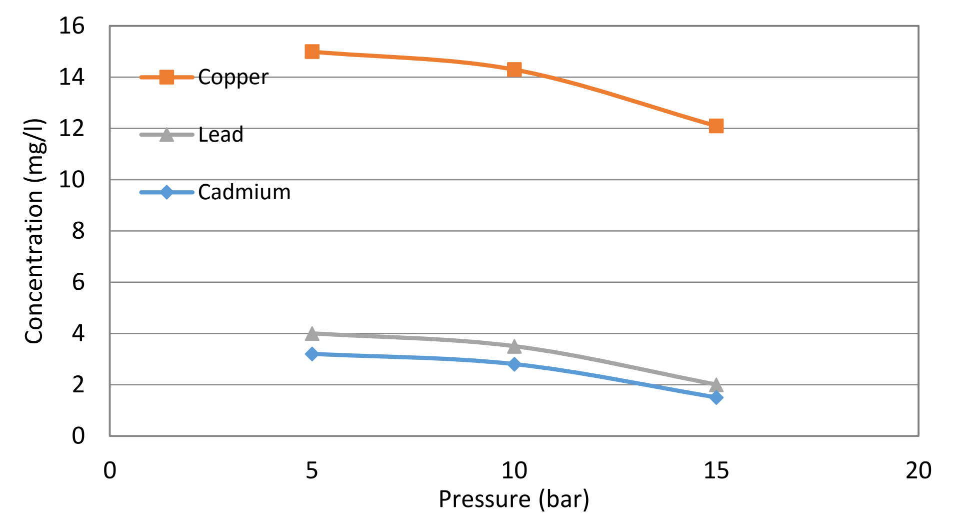

100
99.95
99.9
99.85
99.8
Rejection rate (%)
■ Nitrate
× Sulfate
● Hardness
y = -0.0035x + 99.868
0
1
2
3
4
5
6
7
Membrane number
96
95.5
95
94.5
94
93.5
93
92.5
Rejection rate (%)
y = 0.0903x + 94.58
y = 0.2872x + 93.676
y = -0.2226x + 94.013
■ Lead
◆ Copper
● Cadmium
0
1
2
3
4
5
6
7
Membrane number
100
90
80
70
60
50
40
30
20
10
0
Concentration (mg/l)
☒ Sodium
■ Hardness
y = 8.0806x + 17.839
y = 0.6571x + 8.8667
0
1
2
3
4
5
6
7
Membrane number
4
3.5
3
2.5
2
1.5
1
0.5
0
Concentration (mg/l)
y = 0.0514x + 2.8907
y = 0.1394x + 1.8397
y = 0.4236x + 0.9512
■ Nitrate
× Sulfate
☒ Alkalinti
+ Calcium
0
1
2
3
4
5
6
7
Membrane number

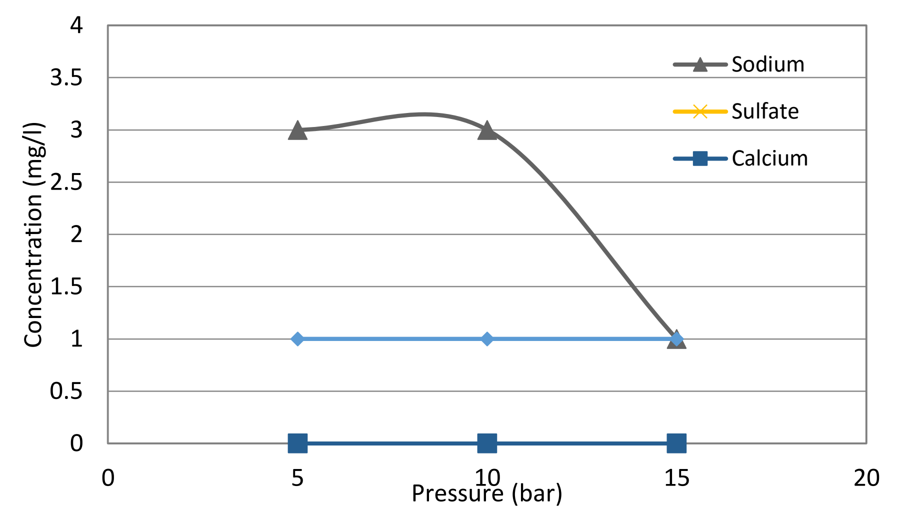
Appendix (7)

Eighth package of experiments: Second pass desalination using NF90 membrane

Test		Q_p	Q_B	Recovery rate	pH	E.C	TDS	Nitrate	Chloride	Sulfate	Alkalinity	Hardness	Calcium	Magnesium	Potassium	Sodium	Cadmium	Copper	Lead
Unit		L/h	L/h	%	0	Micro mho/cm	ppm	ppm as NO_3	ppm as CL	ppm as SO_4	ppm as CO_3	ppm as $CaCO_3$	ppm as Ca	ppm as Mg	ppm as K	ppm as Na	µg/L as Cd	µg/L as Cu	µg/L as Pb
Collected Permeate					6.32	388	240	0	110	0	3	11	0	3	3	65	8	15	10
Pressure(bar)	5	82.9	866.7	8.73	5.99	22	14	0	10	0	3	5	0	1	0	3	3	15	4
	10	137.5	802.4	14.63	5.24	30	11	0	10	0	3	6	0	1	0	3	3	14	4
	15	183.1	770.3	19.21	5.76	12	8	0	8	0	2	4	0	1	0	1	2	12	2



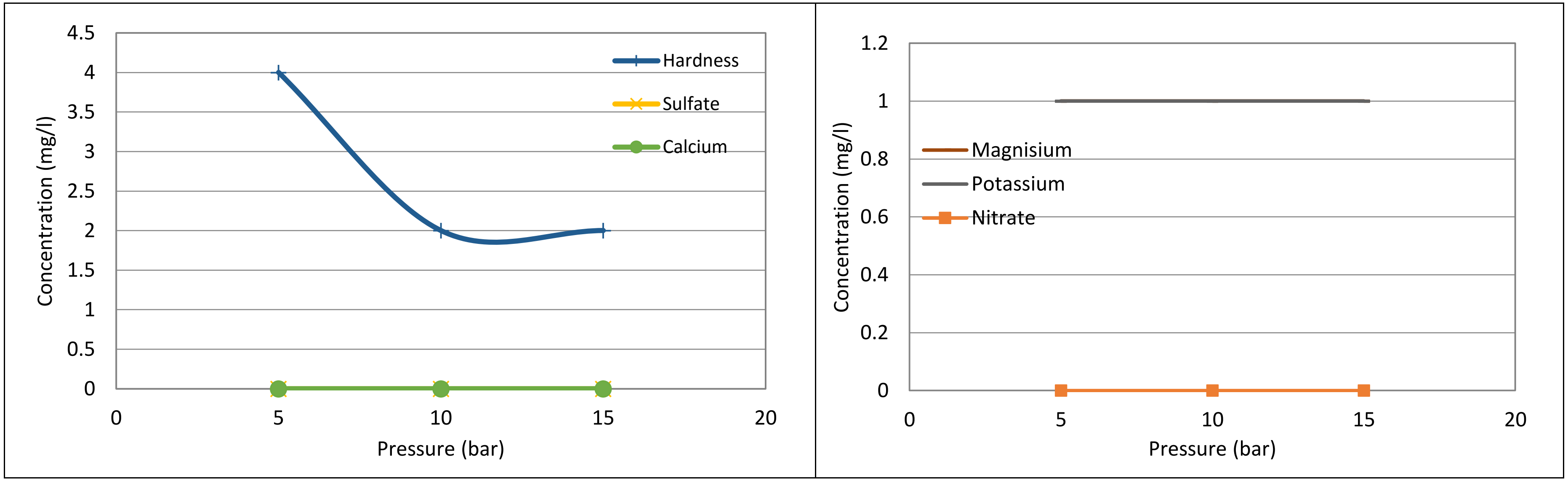

Copper
Lead
Cadmium
Concentration (mg/l)
Pressure (bar)
0
2
4
6
8
10
12
14
16
0
5
10
15
20

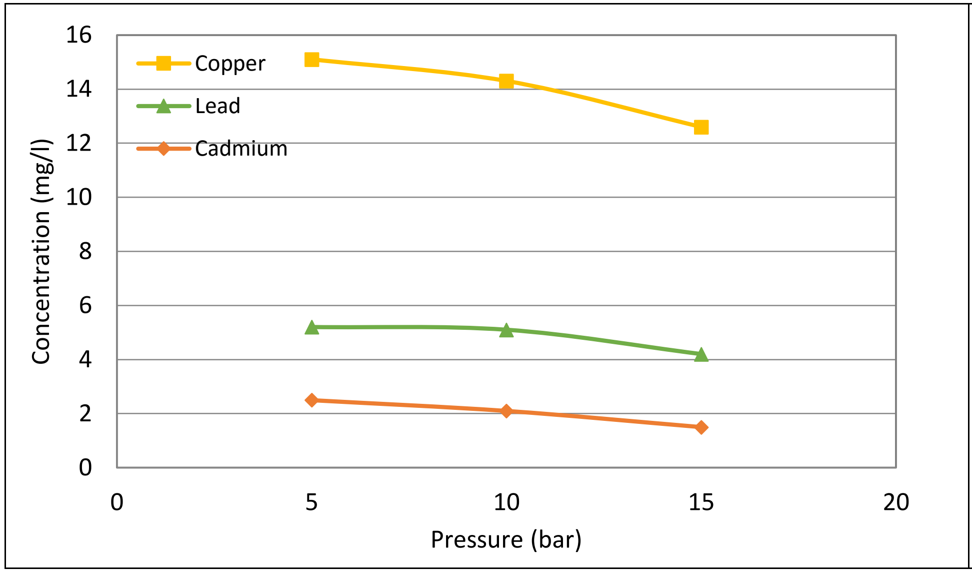

Sodium
Sulfate
Calcium
Concentration (mg/l)
Pressure (bar)
0
0.5
1
1.5
2
2.5
3
3.5
4
0
5
10
15
20

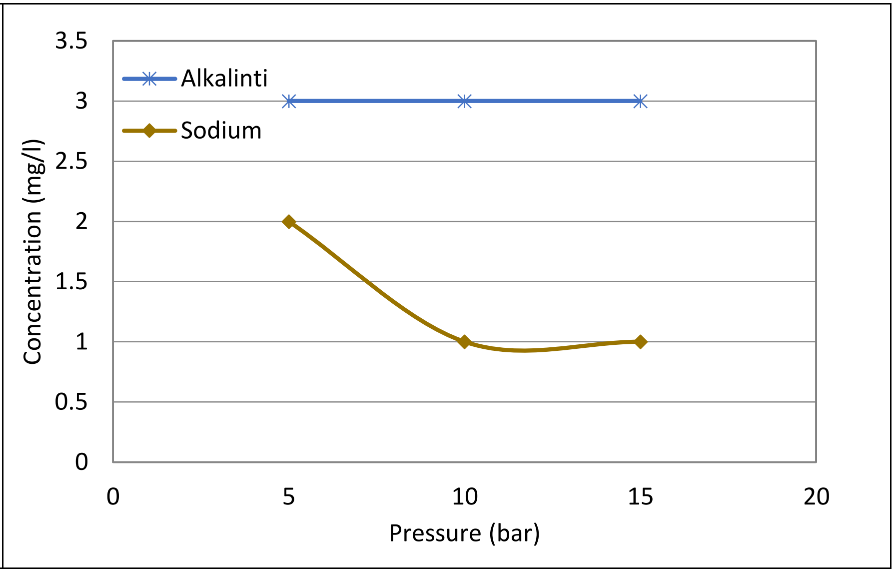
Appendix (8)

Eighth package of experiments: Second pass desalination using RO brackish water membrane

Test		Q_p	Q_B	Recovery rate	pH	E.C	TDS	Nitrate	Chloride	Sulfate	Alkalinity	Hardness	Calcium	Magnesium	Potassium	Sodium	Cadmium	Copper	Lead
Unit		L/h	L/h	%		Micro mho/cm	mg/l	mg/l as NO_3	mg/l as CL	mg/l as SO_4	mg/l as CO_3	mg/l as $CaCO_3$	mg/l as Ca	mg/l as Mg	mg/l as K	mg/l as Na	µg/L as Cd	µg/L as Cu	µg/L as Pb
Collected Permeate					6.32	388	240	0	110	0	3	11	0	3	3	65	8	15	10
Pressure(bar)	5	40.5	927.1	4.19	6.31	20	12	0	6	0	3	4	0	1	0	2	3	15	5
	10	69.9	884.9	7.32	6.1	8	8	0	5	0	3	2	0	1	0	1	2	14	5
	15	102.8	852.8	10.76	6.16	11	7	0	4	0	3	2	0	1	0	1	2	13	4




16
14
12
10
8
6
4
2
0
Concentration (mg/l)
Copper
Lead
Cadmium
0
5
10
15
20
Pressure (bar)


3.5
3
2.5
2
1.5
1
0.5
0
Concentration (mg/l)
Alkalinti
Sodium
0
5
10
15
20
Pressure (bar)