إقـــــــرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

OPTIMAL ENERGY CONSUMPTION DESIGN OF LARGE SEAWATER REVERSE OSMOSIS SYSTEMS

التصميم الأمثل لتقليل إستهلاك الطاقة لأنظمة التناضح العكسي الضخمة لتحلية مياه البحر

أقر بأن ما اشتملت عليه هذه الرسالة إنما هي نتاج جهدي الخاص، باستثناء ما تمت الإشارة إليه حيثما ورد، و إن هذه الرسالة ككل أو أي جزء منها لم يقدم من قبل لنيل درجة أو لقب علمي أو بحثي لدي أية مؤسسة تعليمية أو بحثية أخري.

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The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

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Water Resources Engineering

الجامعة الإسلامية-غزة
عمادة الدراسات العليا
كلية الهندسة
هندسة مصادر المياه

Optimal Energy Consumption Design of Large Seawater Reverse Osmosis Systems

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By:

Taleb F M Seyam

Supervised By:

Dr. SAID M S GHABAYEN

A Thesis Submitted in Partial Fulfillment of the Requirement for the Degree of Master of Science in Water Resources Engineering

The Islamic University - Gaza - Palestine

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بسم الله الرحمن الرحيم

الجامعة الإسلامية – غزة
The Islamic University - Gaza

مكتب نائب الرئيس للبحث العلمي والدراسات العليا هاتف داخلي 1150

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نتيجة الحكم على أطروحة ماجستير

بناءً على موافقة شئون البحث العلمي والدراسات العليا بالجامعة الإسلامية بغزة على تشكيل لجنة الحكم على أطروحة الباحث/ **طالب فخري محمود صيام** لنيل درجة الماجستير في **كلية *الهندسة*** قسم **الهندسة المدنية– هندسة مصادر المياه** وموضوعها:

التصميم الأمثل لتقليل إستهلاك الطاقة لأنظمة التناضح العكسي الضخمة لتحلية مياه البحر

OPTIMAL ENERGY CONSUMPTION DESIGN OF LARGE SEAWATER REVERSE OSMOSIS SYSTEMS

وبعد المناقشة التي تمت اليوم الأحد 12 ربيع الآخر 1436هـ، الموافق 2015/02/01م الساعة الثانية مساءً، اجتمعت لجنة الحكم على الأطروحة والمكونة من:

د. سعيد صالح غباين	**مشرفاً ورئيساً**	....
د. مازن طه أبو الطيف	**مناقشاً داخلياً**	....
د. يونس خليل المغير	**مناقشاً داخلياً**	....

وبعد المداولة أوصت اللجنة بمنح الباحث درجة الماجستير في **كلية *الهندسة*/** قسم **الهندسة المدنية- هندسة مصادر المياه.**

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

والله ولي التوفيق،،،

مساعد نائب الرئيس للبحث العلمي والدراسات العليا

أ.د. فؤاد علي العاجز

إقــــــــرار

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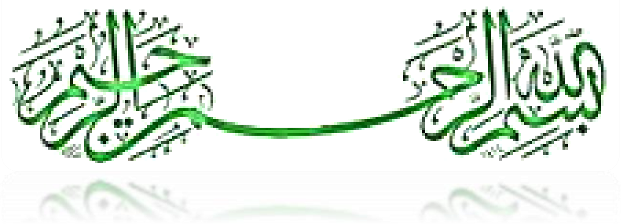
THE HOLY QURA'AN



﴿وَاللَّهُ أَخْرَجَكُمْ مِنْ بُطُونِ أُمَّهَاتِكُمْ لَا تَعْلَمُونَ شَيْئاً
وَجَعَلَ لَكُمُ السَّمْعَ وَالْأَبْصَارَ وَالْأَفْئِدَةَ لَعَلَّكُمْ تَشْكُرُون﴾

النحل آية78

Dedication

To the memory of my father "God's mercy upon"

To my beloved mother

To my dear sisters

To my wife, my son Adam & my two daughters Helen & ceren.

This work is affectionately dedicated

AKNOWLEDGEMENTS

I tremendously grateful for my supervisor Dr. Said M S Ghabayen, without whom I would never have completed this work.

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Above all, I am in debt to ALLAH who has given me the health, strength and patience to

Pursue and Succeed in my career.

Taleb F Seyam

Gaza, 2015

ABSTRACT

The specific energy consumption SEC is the most determinant factor in operation cost of seawater reverse osmosis SWRO systems in desalination plants.

This research aims to study the optimization of SWRO systems performance with minimal specific energy consumption by using the most an advanced technologies with respect to system configuration, pumping system, membrane assembly and energy recovery devices.

This study focuses on both design and actual performance of the membranes by using FILMTEC™ in different stages. The energy consumption was measured in relation with other operating factors such as recovery, feed concentration, productivity, temperature, etc.

ROSA 9.1 software used to investigate the performance of SWRO system, ERI^{TM} PX^{TM} power Model used as supplementary tool to investigate SEC reduction after addition pressure exchanger PX to the system in first pass.

Results of the analysis emphasized on the valuable contribution of the energy recovery devices ERD and high efficiency pumps for increasing water productivity and decreasing energy consumption per cubic meter of water produced. Results showed that using the available advanced technologies and new technical concepts, it is possible now to produce water with energy consumption of reverse osmosis processes close to 3 kWh/m^3.

The results showed that, for the first pass, the effect of using ERD leads to reduction in the SEC from 3.90 down to 2.04 kWh/m^3. The resultant energy saving is 46% at recovery rate (40 - 50%). Finally, an acceptable agreement between actual (Perth case – Australia) and design results of the study has been noticed.

The study concluded that Isobaric ERD such as the PX device can reduce the energy consumption of SWRO system by as much as 46% compared to systems with no ERD.Since energy consumption may comprise as much as 75% of the total operating costs of SWRO plant, it has become almost inconceivable to build SWRO system without using isobaric ERD.

SWRO plants should be arranged in three centers: Pumping Center, Membrane Banks, and Energy Recovery Center to provide a significant reduction in overall water costs.

الملخص

يعتبر استهلاك الطاقة من أهم العوامل التي تؤثر علي تكاليف تشغيل أنظمة التناضح العكسي في محطات تحلية مياه البحر.

ويهدف البحث إلي دراسة كيفية رفع كفاءة أنظمة التناضح العكسي في تحلية مياه البحر مع تقليل استهلاك الطاقة بإستخدام التكنولوجيا المتقدمة المتوفرة في مجال أنظمة الضخ والمرشحات وأنظمة استرجاع الطاقة.

وتركز هذه الدراسة علي كيفية تصميم ورفع كفاءة النظام باستخدام مرشحات من نوع FILMTEC™ في المراحل المختلفة.

وتمت دراسة طرق استهلاك الطاقة من خلال عدة عوامل التي تؤثر في تشغيل المحطات مثل قدرة الإستعادة في المحطة ونوعية مياه البحر والإنتاجية ودرجة الحرارة ..الخ.

ولقد تم استخدام برنامج ROSA 9.1 وذلك للتحقق من كفاءة نظام تحلية مياه البحر؛ كما تم استخدام برنامج ERI™ PX™ Power Model كأداة مساعدة لدراسة تقليل استهلاك الطاقة عند إضافة أنظمة استرجاع الطاقة في المرحلة الأولي في محطة التحلية.

وأظهرت الدراسة من خلال التحليل أن أنظمة استرجاع الطاقة و المضخات عالية الكفاءة تساهم بنصيب لا يمكن إغفاله في زيادة انتاج كميات المياه المحلاة وتقليل استهلاك الطاقة لكل متر مكعب من المياه المحلاة.

وتشير النتائج إلي أن استخدام التكنولوجيا المتقدمة والمفاهيم الحديثة يؤدي إلي تقليل استهلاك الطاقة لما يقارب من 3 كيلو واط للمتر المكعب.

وأظهرت النتائج أنه في المرحلة الأولي عند استخدام أنظمة استرجاع الطاقة تم تقليل استهلاك الطاقة من 3.90 كيلو واط للمتر المكعب إلي 2.04 كيلو واط للمتر المكعب.حيث كان تقليل استهلاك الطاقة بنسبة 46% عند نسبة الاسترجاع (40% - 50%). و تجدر الإشارة أن هناك توافق بين نتائج الدراسة بالمقارنة مع محطة بيرث في أستراليا لتحلية مياه البحر التي هي الآن تعمل وتحت الخدمة.

وخلصت الدراسة إلي أن إستخدام أنظمة إسترجاع الطاقة (مبادل الضغط) يمكن أن يقلل من استهلاك الطاقة بنسبة 46% بالمقارنة مع عدم استخدام أي نظام استرجاع الطاقة في محطات تحلية مياه البحر و بما أن إستهلاك الطاقة يشكل 75% من سعر تشغيل المحطة؛ فإنه من غير الممكن إنشاء محطات تحلية لمياه البحر بدون إستخدام أنظمة استرجاع الطاقة. و إنه عند تصميم المحطات من الأفضل أن تقسم إلي ثلاث تقسيمات: قسم الضخ وقسم المرشحات وقسم إسترجاع الطاقة لتؤدي إلي تقليل ملحوظ في تقليل أسعار المياه المنتجة.

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LIST OF ACRONYMS AND ABBREVIATIONS

Reverse Osmosis	RO
Seawater Reverse Osmosis	SWRO
Specific energy consumption	SEC
Coastal Aquifer Management program	CAMP
Gaza Seawater Desalination Plant	GSWDP
Kilowatt hour per cubic meter	$\mathrm{KWh/m^3}$
Perth Seawater Desalination plant	PSWDP
Energy recovery device	ERD
Reverse Osmosis System Analysis	ROSA
Cubic meter	$\mathrm{M^3}$
Pressure or Work Exchanger	PWE
Dual Work Exchanger Energy Recovery	DWEER
Pressure Exchanger	PX
Parts per million	ppm
Osmotic pressure of seawater	π_s
Pressurized feed water flow rate	Q_f
Permeate water flow rate	Q_p
Concentrate flow rate	Q_c
High pressure	HP
Osmotic pressure of concentrate	π_c
Total dissolved solids	TDS
Variable Frequency Drive	VFD
Pressure Vessels	PV
Energy Recovery Incorporate	ERI
Three Center Design	TCD
High pressure Pump	HPP
Energy recovery system	ERS

Pound per inch	Psi
Pelton impulse turbine	PIT
Work Exchanger	WE
Francis Turbine	FT
hydraulic turbocharger	HTC
Energy recovery turbine	ERT
Turbo charger/ Hydraulic Pressure Booster	HPB
Variable frequency drivers	VFD
Total dissolved solids	TDS
Brackish water reverse Osmosis	BWRO
Clean In place	CIP

CHAPTER (1)

INTRODUCTION

1.1 General

The large scale seawater desalination is an attractive alternative for producing large quantities of potable water in countries suffering from scare natural fresh water resources. Reverse osmosis RO desalination technique, considered one of the fastest - growing techniques in water desalination industry. However, seawater reverse osmosis SWRO desalination still more energy intensive compared to conventional fresh water treatment technologies and the challenges still exist to make this technique more affordable and adaptable for relatively large communities to meet their continuous population growth pressures, industrial development combined with changing climate patterns.

Major latest innovative solutions and technological advances in RO seawater desalination process have been led to a remarkable decrease of desalted water cost. The energy consumption is the most determinant and significant component of final cost of desalinated product water. This due to applying sufficient high dynamic pressure produced by high pressure feed pumps driven by large power consumption motors to overcome the osmotic pressure of the salt solution (seawater), and forces the pure water to pass through semi-permeable membrane.

Typically 50 to 75% of the energy consumed by SWRO plant is used to drive the motors of the high-pressure pumps of the first pass (Mickols et al. 2005). Thus reduction of specific energy consumption SEC has monopolized the focus of technological innovation and research in this sector by taking the full advantages of the highest energy efficient plant design, utilization of high efficiency pumping, energy recovery devices, advanced membrane materials. This integration of advanced technologies and innovations save energy and reduce the cost significantly in full-scale applications

1.2 Research Motivation

The water production cost in a typical RO desalination plant generally consists of the cost of energy consumption, equipment, membranes, labor, maintenance and financial charges, as shown in figure (1.1). Energy consumption is a major portion of the total operating cost of water desalination plant and can reach as high as about (28-50 %) of the total permeate production cost. The energy unit per volume of produced permeate i.e., SEC is significant in RO operation due to the high pressure requirement, which reach up to 1000 psi (70 bar) for seawater (water reuse association, 2011).

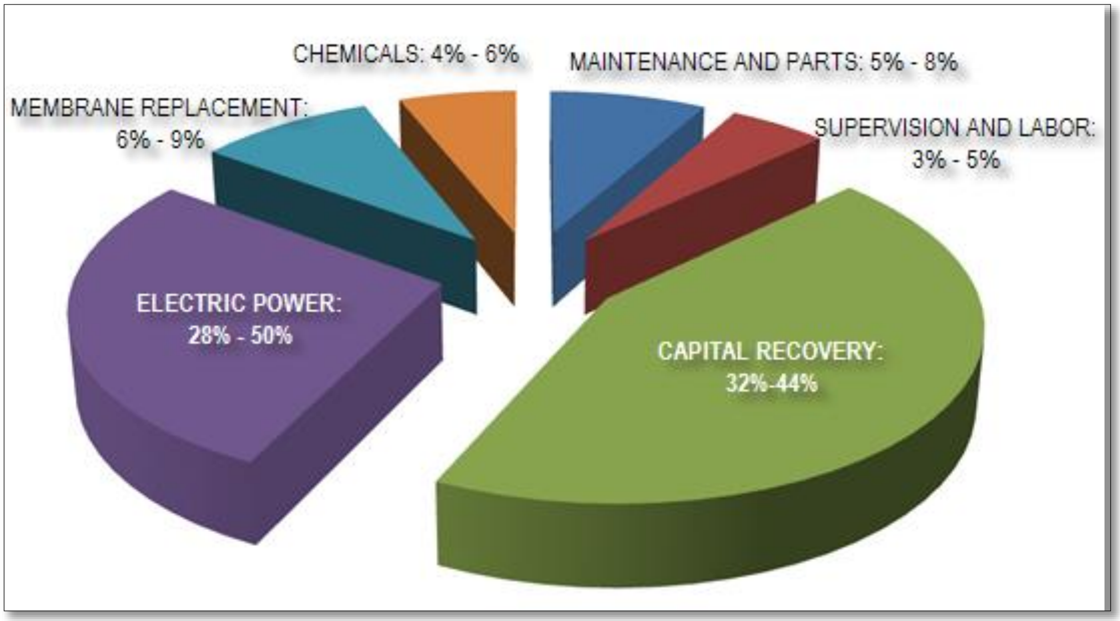


Figure: 1.1 Cost breakdown of desalinated seawater production (Water reuse association, 2011)

The water situation in Gaza strip is disastrous. The only source of water is the ground aquifer, where the water level is decreasing, with increase in water demand for different uses, which reflects seriously in the water quality and quantities in the aquifer (Aiash and Moghier, 2012). Seawater RO desalination is a potential and promising option to alleviate the water crisis in Gaza strip, but general perception is that SWRO is still an energy-intensive process, thus making it expensive and environmentally unsound. But by combining best available technologies, in specific optimal configurations and conditions, SWRO can be now no more energy-intensive than many conventional sources of water.

1.3 Case Study

In accordance with the Coastal Aquifer Management Program CAMP financed by the USAID, it has been identified that the most critical element in bringing the Coastal Aquifer into balance and restoring the viability of the potable water aquifer in Gaza is providing new sources that will offload the seriously depleted groundwater supply. Construction of Gaza Seawater Desalination Plant GSWDP as regional large scale seawater desalination facility to be located at the southern of Gaza strip which proposed as the most visible potential option according to CAMP.

To keep my desk study on track, I considered operation outputs of Perth seawater desalination plant **PSWDP** located in Australia, as a plant in operation similar to GSWDP in capacity and operational Parameters.

1.4 Aim

This study is designed to demonstrate that SWRO is an affordable technology should be adopted as soon as possible to alleviate the water crisis in Gaza strip. The project analyze and study the optimization of the quantitative and qualitative controllable variables / parameters that reduce specific energy consumption in Seawater Reverse Osmosis SWRO system.

1.5 Objectives

Main Goal:

Analysis & optimization of specific energy consumption in a large scale seawater reverse osmosis desalination plants.

Specific Objectives:

- To perform a comprehensive desk study of main SWRO block components in terms of energy consumption.
- To investigate the interaction between energy interrelated parameters in the SWRO main components.
- To review the main innovations and future trends that may minimize energy consumption in seawater reverse osmosis desalination.
- To optimize SEC (KWh/m^3) in large scale SWRO desalination plant with best available advanced technologies.
- To select and present the most energy efficient design for proposed SWRO Gaza desalination plant, with capacity of (**140,000-160,000 m^3/day**).

1.6 Methodology

It is intended to achieve the objectives of the study by following steps:

1. **Literature Review.**

   Revision of all accessible references such as books, case studies and researches related to the subject that investigate in main components of SWRO; different designs and configurations of SWRO plant, high pressure pumping system, membranes and energy recovery devices.

2. **Data interpretation and analysis.**

   After data collection, the data was filtered and interpreted in terms of energy, followed by comprehensive engineering analysis of mathematical models.

3. Quality Control.

Perth seawater desalination plant **PSWDP** located in Australia, was studied in more details, by investigating the mathematical models implied and testing with ROSA software. **PSWDP** has been taken as case study since it is producing 144,000 m^3/d near in capacity of proposed Gaza seawater desalination plant **GSWDP** and one of the most energy efficient SWRO desalination plant worldwide.

4. Optimization

Using projection software **Dow/FilmTec-ROSA** for modeling to optimize **SWRO SEC** (KWh/m^3) to approach the optimal value (< 3 Kw/m^3) in proposed **GSWDP**.

And using ERI^{TM} PX^{TM} power Model - designed by ERI- as assistance tool with ROSA software to optimize the specific energy consumption after introduction the energy recovery devices to the SWRO first pass.

Figure (1.2) shows the flow chat of study methodology start with data collection and interpretation, followed by comprehensive analysis of several main components of SWRO system then using design software to optimize the performance of SWRO system.

Methodology Flow Chart

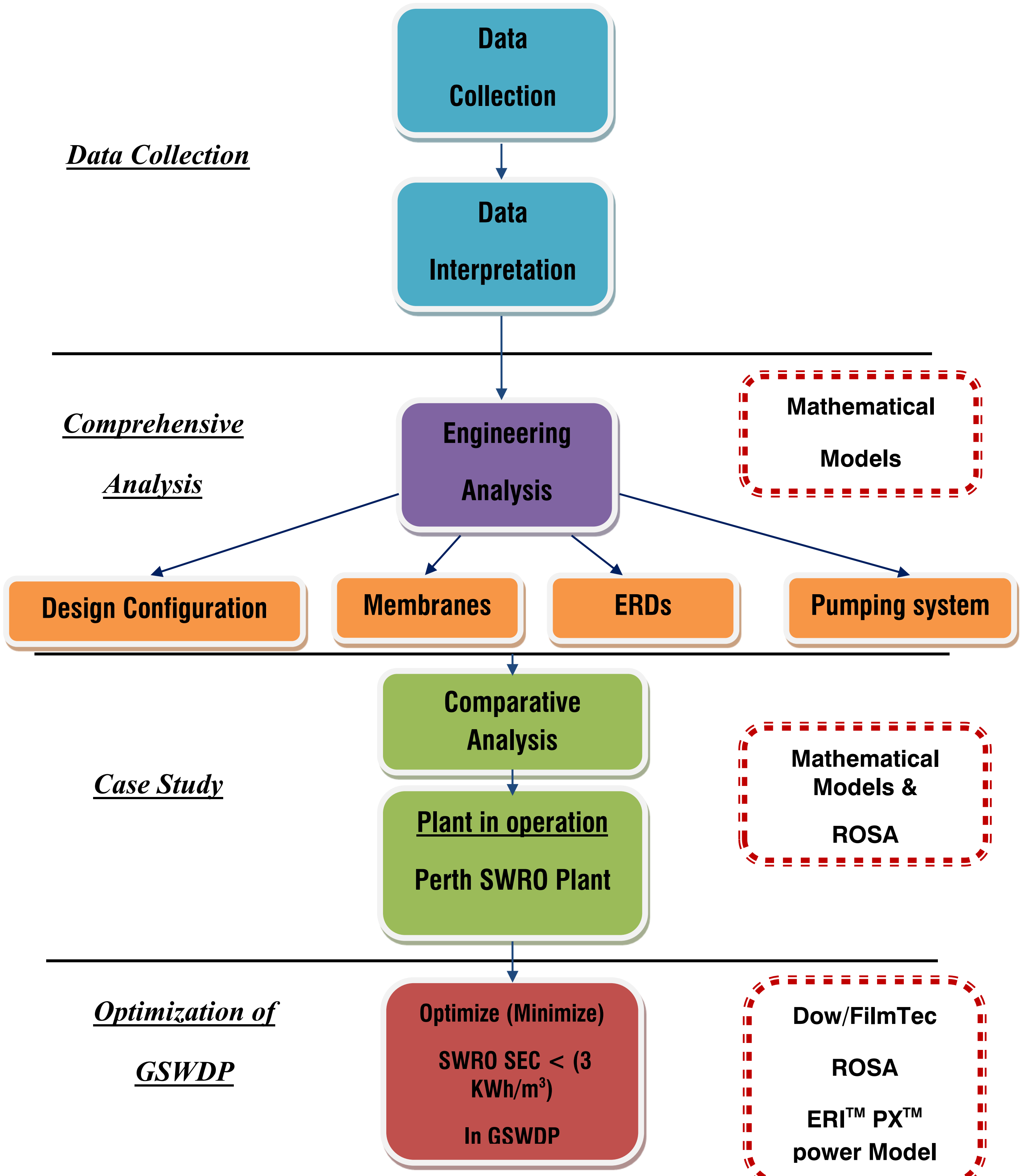


Figure: 1.2 Methodology Flow Chart

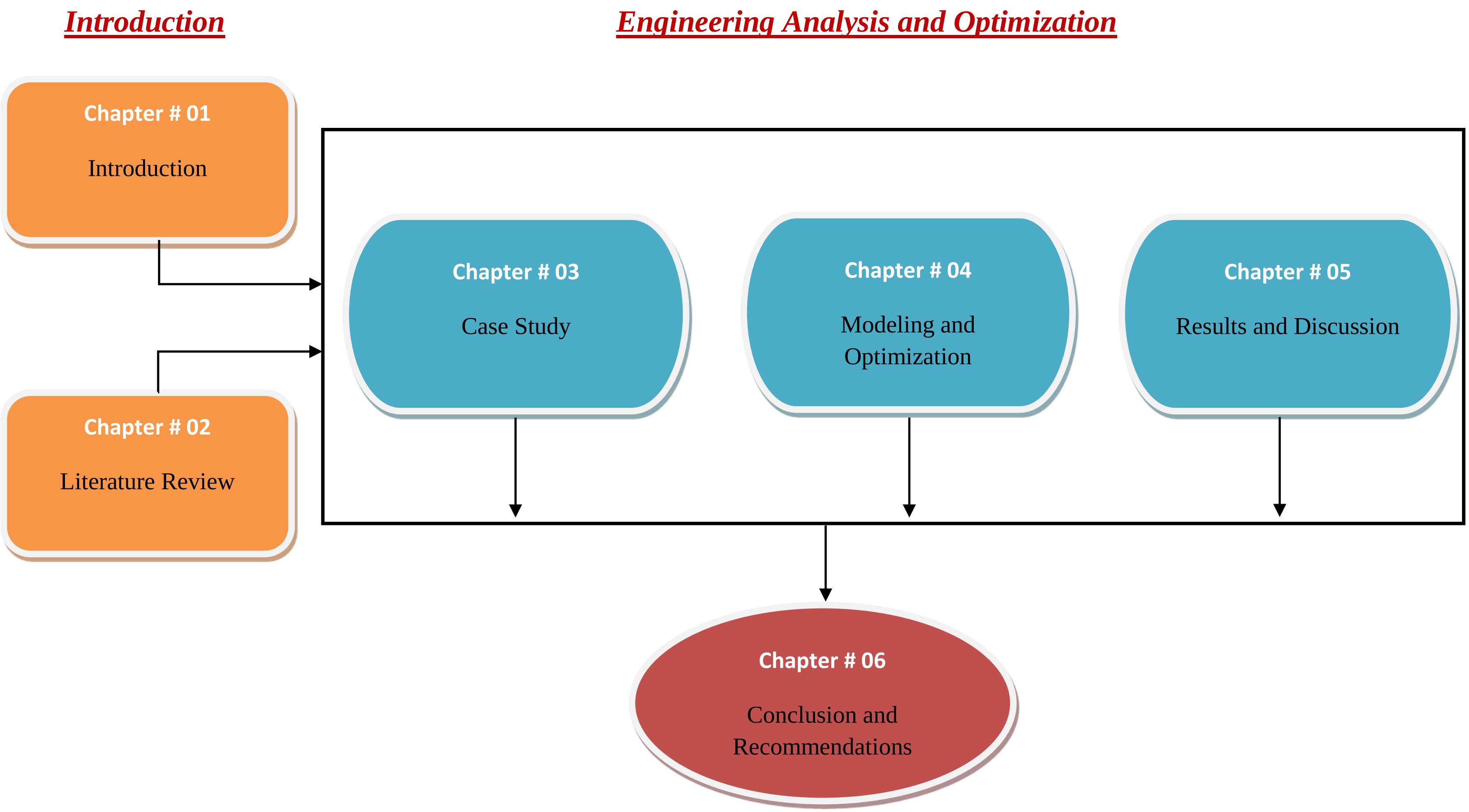


Figure: 1.3 Research profile to develop the most energy-efficient design for large scale SWRO desalination plant.

1.7 Thesis Organization

This thesis has been organized into six chapters.

Figure 1.3 shows the research layout in the development of the most energy efficient design for large scale SWRO desalination plant.

- **Chapter One (Introduction):** general introduction is followed by problem identification, study objectives, methodology, and tools used in order to achieve the objectives and finally, a plan for thesis outline.
- **Chapter Two (literature Review):** covers a general literature reviews published in regard to energy consumption in SWRO desalination plants.
- **Chapter Three (Case study):** Perth seawater desalination plant has been taken as a case study.
- **Chapter Four (Modeling and Optimization):** express the mathematical equations for main effective parameters of energy consumption reduction in SWRO plant. And using projection software such as Dow/Film Tec - ROSA to investigate the interactions & effects of several parameters of SWRO system.
- **Chapter Five (Results and Discussion):** Study the different design configuration and using energy recovery devices to investigate the most effective and efficient for different configurations and arrangements of SWRO plant components.
- **Chapter Six (Conclusion and Recommendations):** The conclusions and recommendations of the study are stated in this chapter of the thesis.

CHAPTER (2)

LITERATURE REVIEW

2.1 Introduction

In the last few years RO seawater desalination technology has gone through a remarkable transformation. The number and capacity of large RO plants have increased significantly. Systems with permeate capacity up to 300,000 m^3/d are currently being built. In a parallel shift the capital and operating cost has decreased. Desalted water cost, supplied to customer, decreased from \$2.0/m^3 in 1998 down to 2004 price of about \$0.5/m^3 (Wilf and Bartels, 2004).
In 2016, the global water production by desalination is projected to exceed 38 billion m^3 per year, twice the rate of global water production by desalination in 2008 (Schiermeier, 2008).
The drivers behind these economical improvements are competition and improvement in the process, advanced membrane technology and increased efficiency of energy recovery devices.
Minimum specific energy consumption can be acquired by optimizing operating parameters, Reduced feed flow and slightly increased operating pressure yields higher driving force in the brine channel. Further reduction in specific energy can be achieved by enlarged feed spacer thickness and shorter filament length. This gives less pressure drop and consequently, more water flux (Sassi and Mujtaba, 2010).

From a process engineering perspective, the RO process performances can be improved by:

- Enhancing the efficiency of the unitary equipment used in the RO process (pretreatment, pumps, energy recovery devices, high permeability membranes, etc.).
- Improving the RO process layout and adapting the operating conditions to this layout.

The technical characteristics of the RO process configurations (total water recovery rate, electricity consumption, number of pressure vessels, installed power of pumps and pressure exchangers, lengths and diameters of the connecting pipes) are calculated as a function of the project specifications (e.g. permeate production capacity).The plant electricity consumption by cubic meter (m^3) of potable water produced and the plant water recovery rate in m^3 of potable water by

m^3 of feed water are deduced from the calculations of these successive treatment steps (Vince et al., 2008).

2.2 Design Configuration of SWRO

The design and configuration of membrane units have a significant effect on the performance and economics of RO plant (Wilf and Bartels, 2005). In the past, membrane units for seawater were usually configured as two stages with six elements per pressure vessel. The two-stage system resulted in a high feed and concentrate flow, which reduced concentration polarization at the expense of a greater feed pressure needed to compensate for the increased pressure drop across the RO train. Design efforts to reduce power consumption resulted in the use of single-stage configurations for high salinity feed water applications, and in some cases, the use of seven (or) eight elements per pressure vessel is preferred (Wilf and Bartels, 2005; Petry et al., 2007). The pressure drop reduction in using a single-stage rather than a two-stage system was reported to result in a 2.5% lower power requirement (Wilf and Bartels, 2005).

More recently, further reduction in RO desalination cost has been shown to occur from optimal process configuration and control schemes. Theoretical cost minimization framework have been developed and experimentally implemented using a controller to quantify the effect of energy cost with respect to membrane cost, brine management cost, energy recovery, and feed salinity fluctuation (Zhu et al., 2009b, 2010).

A control system utilizing real-time sensor data and user defined permeate flow requirements have been implemented to compute in real-time the energy-optimal set-points for controlling concentrate valve position and feed flow rate (Bartman et al., 2009, 2010). Implementation of the control system demonstrated the ability to achieve energy-optimal operation of the RO system close to the theoretically predicted energy consumption curves.

When stringent water quality requirements mandate the use of multi-pass RO, the overall power consumption of the RO system can be lowered if a portion of the first pass permeate is pumped to the second pass (Zhu et al., 2009). Since permeate produced from the front-end elements is lower in salinity than permeate produced at the back-end elements, lower feed pressure is required for the second pass when the front-end permeate is utilized as feed to the second pass. In a multi-pass system, the lowest energy consumption is obtained when membranes with the highest salt rejection is used in the first-pass (Zhu et al., 2009a). In another study, various mixing operations between feed, concentrate, and permeate streams were evaluated to assess their potential on energy usage (Zhu et al., 2010a). It was determined that various mixing approaches may provide certain operational or system design advantages but they do not provide an advantage from an energy usage perspective.

A novel design modification to reduce pressure drop across membrane elements is the use of a pressure vessel with a center port design (van Paassen et al., 2005). In this innovative configuration, feed water enters the pressure vessel through two feed ports on each end of the pressure vessel in the first stage. The concentrate is collected through a middle port and flows to a similar port on the pressure vessels in the second stage. Thus, the flow path is reduced by half and although the membrane unit has eight elements per pressure vessel, the flow path length is reduced to four elements per stage, creating a lower pressure drop that lowers the feed pressure.
A 15% reduction in the feed pressure has been reported using the center port design when compared to a conventional side port design (Wilf, 2010). The disadvantage of the center port design is the potential for scaling due to excessive concentration polarization. Thus, pilot testing and long-term operational data are recommended before considering implementation of the center port design in order to determine the influence of water quality variations on feed water recovery.

Reduction in energy consumption for RO systems treating high salinity feed water has also been achieved by using a two stage hybrid system with concentrate staging (Veerapaneni et al., 2005). The first stage consists of high rejection brackish water membrane elements (or) high permeability seawater membrane elements. The second stage consists of standard seawater elements. Using a two-stage system with brackish (or) low-pressure seawater membranes in the first stage lowers feed pressure requirements due to lower membrane resistance (Veerapaneni et al., 2007). As most of the permeate is produced in the first stage with the high permeability membranes, the pressure of only a small fraction of the remaining flow is boosted, resulting in significant energy savings.

Energy consumption is also reduced by minimizing the pressure drop across membrane elements .An approach by which to reduce the axial pressure drop in membrane elements involves the use of a novel feed spacer design that reduces the hydraulic pressure drop in the RO elements (Subramani et al., 2006; Guillen and Hoek, 2009). The feed spacer pattern used in most spiral wound membrane elements causes a variation in the flow path of the feed water resulting in a higher axial pressure drop than flow in an open channel (Guillen and Hoek, 2009). Although feed spacer geometry was found to have a marginal impact on mass transfer, thinner spacer filaments spread apart substantially reduced hydraulic pressure losses. In addition, certain non-circular spacer filament shapes produced lower hydraulic losses when compared to conventional circular spacer filament shapes (Guillen and Hoek, 2009). Although various feed spacer geometries have been shown to reduce hydraulic pressure loss in RO elements, actual data from pilot-scale and full-scale operation are still minimal since spiral wound elements with novel feed spacer configurations are not readily available. Commercialization of feed spacers that reduce the axial pressure drop across membrane elements could potentially reduce the feed pressure requirements during RO seawater desalination.

A plant design approach for improving the economics of desalination and at the same time reduce the impact on environment due to brine discharge is the co-location of membrane desalination plants with existing coastal power generation stations (Voutchkov, 2004). In this approach, overall desalination power demand and associated costs of water production are reduced as a result of the use of warmer source water. The cooling water discharged from the condensers in a power plant is 5-15 ^{o}C warmer that the source ocean water. When this water is used by the RO plant, 5-8% lower feed pressure is required to desalinate the water when compared to desalination of colder source ocean water. This approach also has the advantage of sharing a common intake facility. In the Middle East, RO and thermal-based technologies are combined to provide a hybrid design (Cardona and Piacentino, 2005). Such hybrid designs not only result in capital savings by sharing a common intake and outfall facility but also have a 40-50% increase in water production related to pre-heating of feed water to the RO plant.

The core hydraulic module of a single-stage SWRO plant is defined as the arrangement of a high-pressure pump (HP) combined with an energy recovery system (ERS). According to this definition, the core hydraulic module pressurizes the pretreated feed water and recovers the energy contained in the brine flow. Pretreatment fluid handling and permeate transport are not included. A schematic representation of three different core hydraulic modules using different ERS are shown in Fig 2.1.

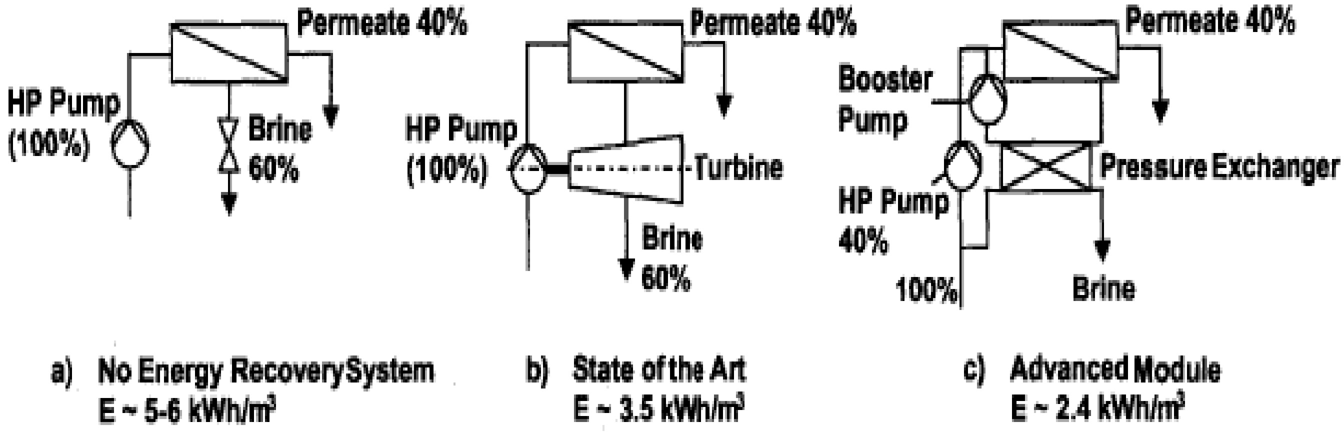


Fig 2.1: Schematic representation Pumping arrangement in RO plant (Kochanowski and Bross,2004)

Fig 2.2: Ashkelon SWRO plant (Goichon, 2007)

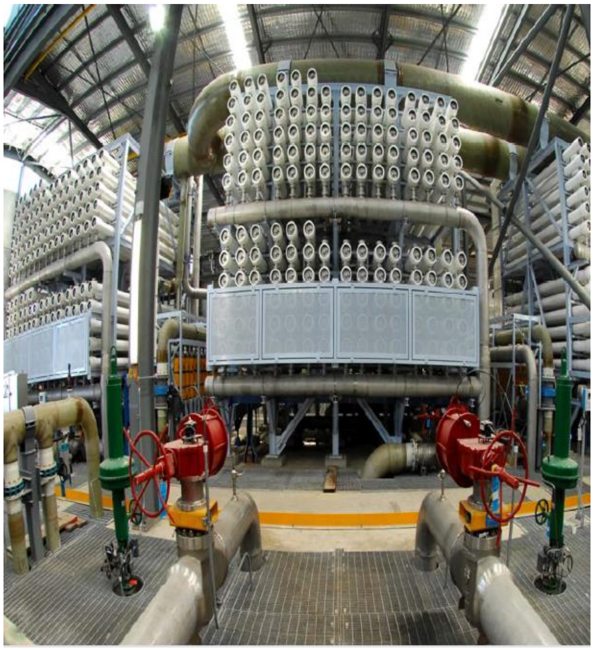


Fig 2.3: Perth SWRO plant (Hoang et al., 2009)

A centralized pump and energy recovery system – the Three Center Design TCD, comprising a pump center, a membrane center and an energy recovery center, has the flexibility required to change water production and power demand in a smooth and effective way, without harming the desalination equipment. This centralized pump and energy recovery system, together with small membrane banks, is an effective solution for large desalination plants. The system's ability to level the power demand is related to the ability of the Energy Recovery System ERS to change the brine flow smoothly, across a broad range, without changing the high pressure pump flow and losing pumping efficiency. The best way to achieve this is to mechanically separate the energy recovery system from the pump system. This allows the change in flow without having to stop and start equipment (Voutchkov, 2013).

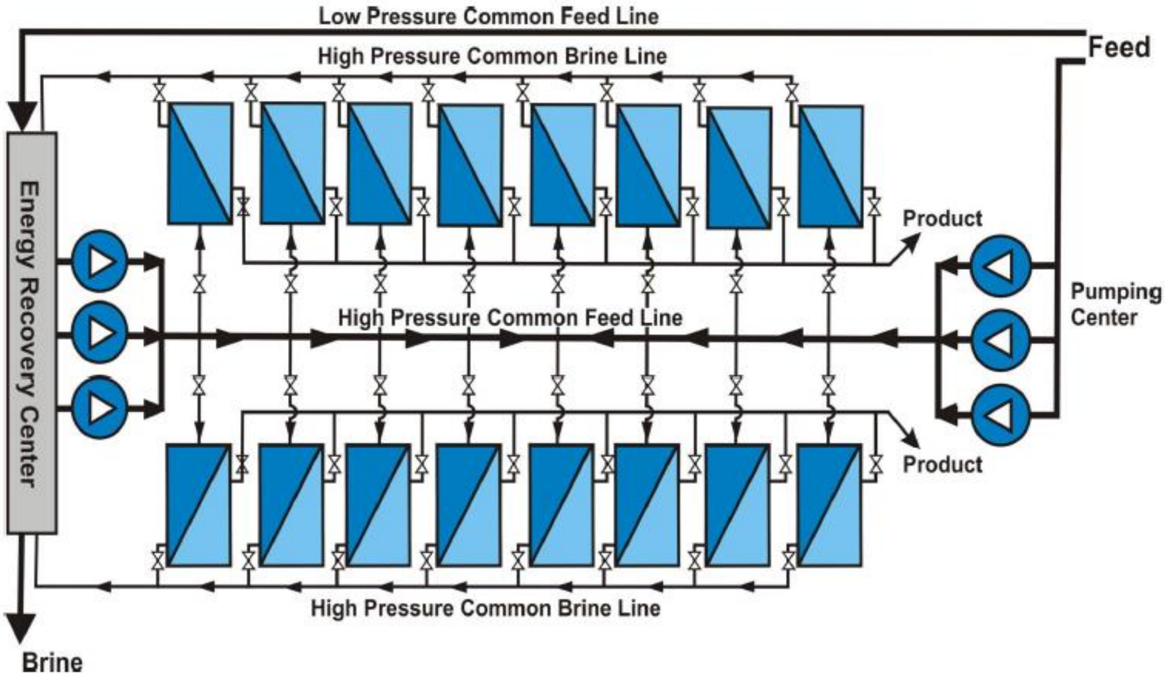


Fig 2.4: SWRO three center design TCD plant (Voutchkov, 2013)

Designing an efficient RO desalination system connected to many variables, such as, feed flow rate, operating pressures, recovery rate, the type of membrane element and its geometry (i.e. spacer geometry) and RO system configuration drive (Sassi and Mujtaba, 2010).

RO process design requires at first to model the unitary equipment composing the process, the most important of which being the RO membrane. Analytical models have been developed to describe the transport phenomenon across the RO membrane. These membrane models are then combined to model the complete RO process. RO process design software were developed by membrane constructors such as ROSA$^{\copyright}$ from FILMTEC$^{\text{TM}}$ or IMS Design$^{\copyright}$ from Hydranautics$^{\text{TM}}$, these software allowed to test flexible RO configurations for different commercial membranes. Where a first step toward process optimization is performing the sensitivity analysis (Vince et al., 2008).

When developing new processes, the conceptual process design consists in identifying the best process configurations in a given context, so that they be detailed by process engineers. A process configuration corresponds to a list of equipment interconnected in a given process layout, for which specific sizes and operating conditions are defined. The process design is realized in several steps. The process synthesis consists in systematically generating process configurations. The process characterization represents the performances evaluation of the generated process configurations while the process optimization aims at selecting the best configurations according to a given objective function (El-Halwagi, 1997).

RO process design therefore requires three key components:

- The technical modeling of RO equipment and a systematic method for RO process synthesis.
- Accurate performances indicators for RO process characterization.
- An optimization procedure for RO process optimization problem (Vince et al., 2008).

2.3 Pumping System

With respect to pumping system, energy is predominantly consumed from operation of primary feed pumps; second pass feed pumps (as required), pretreatment pumps, product water, transfer pumps, chemical feed pumps, and water distribution pumps. The distribution of power usage in a two-stage seawater RO system more than 80% of the power is required for the operation of the primary feed pumps (Wilf and Bartels, 2005). Although the flow and head of a pumping system are determined by the design specifications of the RO system, the selection and operation of pumps and other elements of a pumping system play an important role in reducing overall energy usage in the plant.

To achieve the highest possible pumping efficiency, several procedures are performed including: **(1)** verifying energy efficient operation of the pumping system, **(2)** utilizing a premium efficiency motor, and **(3)** utilizing a variable frequency drive (Manth et al., 2003). To achieve an energy efficient operation, a pump's speed must fall within a specified range for optimal efficiency or the best efficiency point (Veerapaneni et al., 2007). The use of high speed and high flow pumps at lower total dynamic head provides the optimal speed needed for highest efficiency. To accommodate the variability of feed pressure with time (due to salinity and temperature fluctuations) without the necessity to throttle high pressure pumps or energy recovery devices, a variable frequency drive is often incorporated into the electric motor unit that drives the high pressure pump (Torre, 2008). All of the above mentioned pumping methods have been demonstrated to significantly improve efficiency and reduce energy requirements at full scale.

Incorporating a booster pump for feeding the second stage to obtain higher flow and operate with a higher conversion, and to use the latest membranes generation, which are able to support higher pressures than in the previous stage (Sadhwani and Veza, 2008).

The installations of inter-stage booster pumps appear to be a “win-win” option from an economic and point of view. With a booster pump, the 2nd stage can be operated in nominal hydraulic conditions, thus leading to a smaller installed membrane area and to a higher total recovery rate; therefore reducing the electricity consumption and the investment costs (Vince et al., 2008).

It is found that considerable reduction in pumping cost around 20% is achievable. Furthermore, commercial module designs might be further refined in order to reach more economic improvements for RO processes subject to technical limitations (Sassi and Mujtaba, 2010).

The intake pumping depends on the feed water flow rate and on the type of water intake (beach well, open water intake…).

The amount of power needed to drive desalination in SWRO plants has declined dramatically in the past 40 years. This decrease in energy consumption is attributed to continual technological improvements, including higher-permeability membranes, installation of energy recovery devices, and the use of more efficient pumps. The potential to operate the desalination step at an energy consumption rate of 1.8 kWh/m^3 using new, high-permeability SWRO membrane elements has recently been demonstrated on a controlled pilot-scale system at 50% recovery (MacHarg, et al., 2008).

Early SWRO systems consumed as much as 20 kWh/m^3, by the mid-1980s, through improvements in the achievable recoveries of RO membranes and efficiencies of the pumping systems and energy recovery systems, these numbers were reduced to as low as 8 kWh/m^3.

Although these dramatic improvements, SWRO was still energy intensive and was only practical in special economic zones and/or where energy was cheap.

Energy still accounted for as much as 75% of the total operating costs of SWRO systems. For this reason the RO industry re-doubled its effort through the 1990s to create improvements in the membranes, energy recovery and pumping systems and towards the end of the decade, had achieved energy consumption levels as low as 3.5 kWh/m^3.as shown in (Fig. 2.5) (Stover and Grisp, 2008).

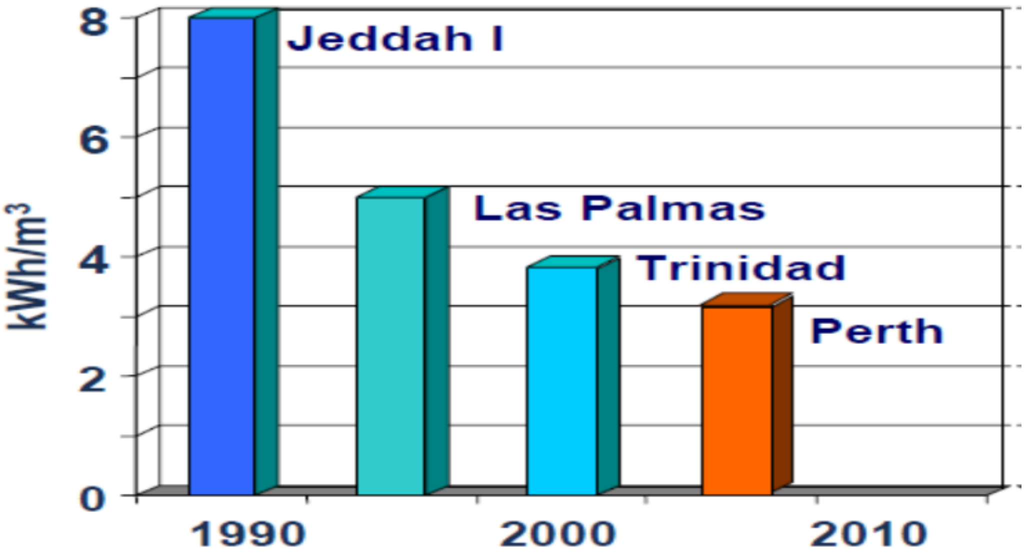


Fig 2.5: Evolution of SWRO energy consumption (Stover and Grisp, 2008)

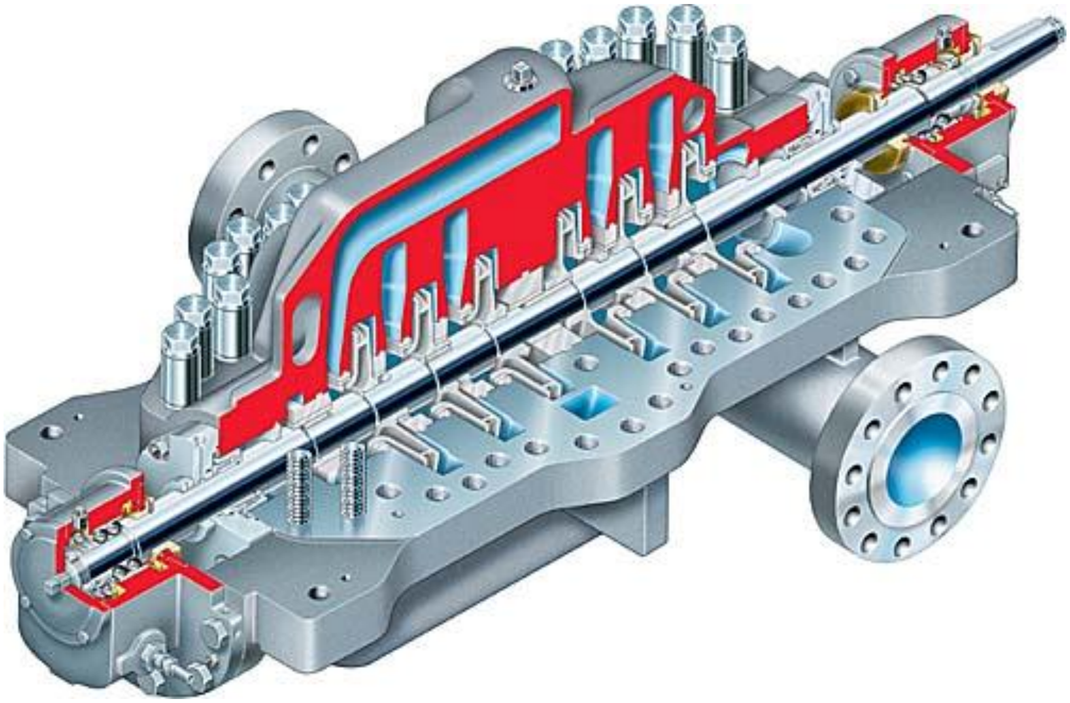


Fig 2.6: Horizontal split-case multistage pump (Source: Flowserve.)

Typically 50% - 75% of the energy consumed by an SWRO plant is used to drive the motors of the high-pressure pumps of the first pass (Mickols et al., 2005). Isobaric ERDs reduce the load on these pumps using the energy contained in the first-pass membrane reject stream.

The pumps have high efficiency alone is not enough for a pumping system to work in maximum efficiency. Working in maximum efficiency of a pumping system depends not only on a good pump design but also a good design of the complete system and its working conditions. Otherwise, it is inevitable that even the most efficient pumps in a system that has been wrongly designed and wrongly assembled is going to be inefficient (Kovats DA et al., 1964).

The purpose of the plant designer must be to find the core pumps running as closest as possible to the best efficiency point. Those pumps running continuously with the biggest portion of total absorbed power, the LP booster pump and the high pressure RO feed pump (Torre, 2007). Values regarding the high pressure pump selection as indicated in table 2.2:

Table 2.1: Commercial high pressure pumps with its corresponding capacities and efficiencies. (Torre,2007)

Capacity	**HPP efficiency**	**High pressure pump**	
		No. of stages	**Discharge flange**
500 – 550 m^3/h	82%	6	6"
650 – 750 m^3/h	85%	5	8"
950 – 1050 m^3/h	86%	4	10"
1200 – 1300 m^3/h	86.5%	3	12"
1600 – 1700 m^3/h	87%	2-3	12"
2200 – 2400 m^3/h	88%	2	14"

2.4 Membrane Assembly

Significant improvements in the salt rejection capacity and permeability of RO membranes for treating high salinity feed waters have been achieved in recent years. In 1980s, seawater RO systems consumed more than 26 kWh/m^3. Today, seawater RO systems consume on average only 3.4 kWh/m^3. The minimum theoretical energy use (50% recovery) is about 1.08 kWh/m^3 for seawater desalination (Voutchkov, 2010). Thus, there are further avenues for improving the permeability of RO membranes using novel membrane materials such that the energy consumption is minimized. But, the new generation membranes must provide at least double the permeability of current generation RO membranes. This is based on a recent approach to determine the minimization of energy costs by improving membrane permeability (Zhu et al., 2009). A dimensionless factor was used to reflect the impact of feed water osmotic pressure, salt rejection requirement, membrane permeability, and purchase price of electrical energy and membrane module. It was estimated that unless the permeability of the RO membrane is doubled and the capital cost of pressure vessels directly impacted by a lower membrane area requirement, further improvements in seawater RO membrane permeability is less likely to significantly reduce the cost of desalination. New generation RO membrane which show promise in providing more than double the permeability of currently available RO membranes. New generation RO membranes offer reduced feed pressure requirements while maintaining rejection. Today’s high productivity membrane elements are designed with two features that include more fresh water per membrane element and higher surface area and denser membrane packing (Voutchkov, 2007).

Feed with low salt concentration produced 40% higher recovery ratios compared to that produced by high feed (5000 ppm) salinity. This is a consequence of the much higher driving force for the same exerted pressure to the feed. This is due to the fact that the osmotic pressure is proportional to the feed salt concentration (Sassi and Mujtaba, 2010).

The feed channels of spiral wound element are flat. Feed stream flows along the channel parallel to the central line of the module and the curvature of membrane module was reported to have insignificant effect on system's performance (Van der Meer et al., 1998).

The reduction of the membrane renewal cost due to high flux operation is always higher than the cost increase of electricity consumption. Achieving the minimum electricity consumption is therefore economically inefficient because it leads a membrane renewal cost higher than the power cost reduction (Vince et al., 2008).

The electricity consumption increases proportionally with the flux, so that the marginal power cost is considered to be constant as a function of the flux. (Vince et al., 2008).

It was observed that the water recovery ratio increases with the number of elements in the pressure vessel due to increased membrane area. There was a sharp increase at lower number of elements and a slow increase at higher number of elements. This was due to the salt build up on the brine channel as flux increases. Therefore adding more elements after certain limit not worthy (Sassi and Mujtaba, 2010).

Feed spacer channel can affect RO performance significantly, compared to that with slit feed channel. Even though the pressure drop is increased, the mass transfer is enhanced, concentration polarization factor on membrane surface is reduced, and the specific energy consumption is reduced (Sassi and Mujtaba, 2010).

The recovery rate of fresh water increases with the increase of mesh length until a turning point at specific mesh length. Small mesh length has the advantage of more turbulent flow and consequently the polarization phenomenon is decreased. On the other hand smaller mesh length has the drawback of higher pressure drops along feed channel and therefore less water flux (Sassi and Mujtaba, 2010).

In accordance with the papers reviewed, the membrane salts permeability is considered to be constant (Gupta, 1985).

2.5 Energy Recovery Devices (ERD)

The subject of energy efficiency in the large seawater desalination plants, the first action carried out in the Canaries has been to replace the energy recovery system traditionally used till the end of the 90s, where the solution planned in the first plant designs was to install a reversed pump which operates with the brine pressure and flow. Afterwards with the appearance of the "Pelton" turbine which had a higher efficiency in energy recovery, the reduction in energy consumption in the desalination plants has been spectacular and notable (Fariñas Iglesias, 1999).
Energy consumption for RO desalination processes is reduced by using energy recovery devices (ERD) that recover energy from the RO concentrate (Andrews and Laker, 2001). Before the concentrate stream is sent for disposal, pressure from the stream is recovered by passing it through an ERD. The fraction of power recovered depends on the type and efficiency of the equipment used. Class I devices use hydraulic power to cause a positive displacement within the recovery device, and the hydraulic energy is directly transferred in one step (Greenlee et al., 2009).The main function of an energy recovery device is to improve energy efficiency by harnessing spent energy from the reject and delivering it back to the feed.

Existing energy recovery systems can be divided in two groups: First group use the principle of positive displacement and Commercial examples of such systems are Energy Recovery, Inc.'s Pressure Exchanger (PX), Desalco's Work Exchanger Energy Recovery (DWEER).

Most of the positive displacement devices achieve relatively similar net energy transfer efficiencies between (91-96%) over the entire flow range of the systems (Greenlee et al., 2009).

Second group use the principle of centrifugal force to convert brine pressure to mechanical power, such as energy recovery turbines (ERT), work exchangers (WE),Pelton impulse turbine (PIT), Francis turbine (FT) or reverse running turbine, back-running pumps and hydraulic turbocharger (HTC), These devices operate on the whole flow with reported efficiency range (70– 85%) depending on capacity (Greenlee et al., 2009).

2.5.1 Francis Turbines (Reverse Running Pump)

Francis Turbines (FT), (known as *reverse running pumps*) belong to the second class of ERDs, i.e. hydraulic to mechanical-assisted pumping, these devices were the first to be employed in SWRO municipal scale desalination plants. Pelton wheels later replaced these in 1980s because of their higher efficiency (Stover, 2007).

The earliest identified disadvantage of (FT) was that the flow range and pressure required for achieving maximum efficiency of operation was narrow and limited. In addition, these ERDs did not generate energy until the design condition reached about 40% (Farooque et al.,2008). In SWRO desalination plants, especially those in the Middle East and similar regions, variations in temperature of the place and changes in membrane permeability occurring due to fouling of the membrane or due to ageing, inversely affect the efficiency of these devices (Farooque et al.,2008). They are also difficult to control and pose a significant challenge in maintenance. The hydraulic energy that is recovered by these devices is mechanically transferred to the driver, similar to the Pelton wheel. The assembly involves a clutch between the turbine and the pump (Mirza, 2008). The (FTs) were inefficient and the amount of energy consumed increased with change in the operation conditions. They were also inefficient for a low range of flow. Because of the disadvantages of these devices, they were replaced with devices that transfer the pressure to feed water from reject pressure directly & more efficiently (Gottberg et al., 2005).

2.5.2 Pelton wheel

Pelton wheel was invented during the 1850s. Originating in San Francisco, it is a kind of water wheel. The Pelton wheel used in SWRO desalination plants is easy to operate. It has an input nozzle through which high-pressure feed is directed onto the buckets of the wheel. The nozzle is designed such that the entire kinetic energy of the pressurized feed is converted to mechanical energy manifested as rotation (Avlonitis, et al., 2002). A nozzle valve is used to direct a jet of high pressure RO concentrate onto the bucket (blades) turn the Pelton wheel. By coupling the shaft of the Pelton wheel to a motor or apump, this energy can be used to reduce the electrical energy that is needed to pump the RO feed water. The buckets, (also referred to as vanes) of the wheel are arranged in series around the shaft, which intercepts the feed stream (Pique, 2000). The pump driven by the Pelton wheel turbine enhances the pressure of the feed before it enters the HPP, thereby decreasing the energy consumption (Hajeeh,et al., 2002).The efficiency of the Pelton wheel remains constantly high even during variations in the pressure and flow of feed. One significant challenge, however, is the design and maintenance of metal parts, as they are easily corroded when exposed to seawater (Pique, 2000).

Development of this technology over the past two decades has led to the widespread use of typical device efficiency ranges between (84 - 90%).

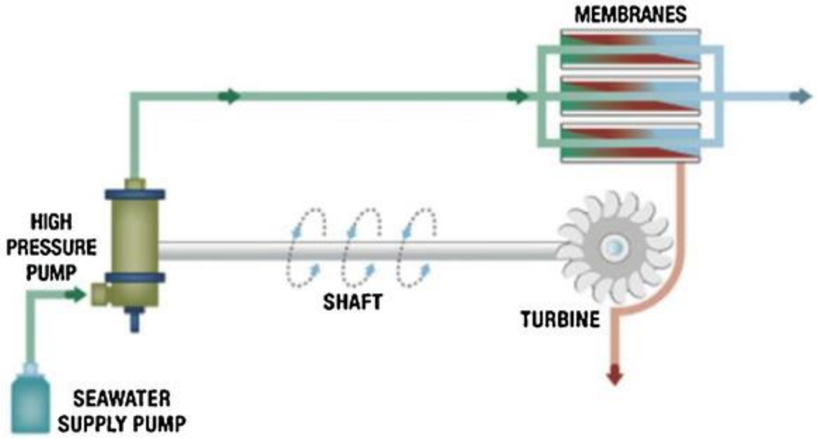


*Fig 2.7: **Pelton wheel turbine (El-Ghonemy, 2012)***

A common characteristic of the Pelton wheel and the (FT) is that these transfer the energy recovered from brine back to the HPP via the shaft. Evidence suggests that the energy efficiency of a desalination plant using a centrifugal HPP, coupled with a Pelton wheel, increases with an increase in the recovery percentage. Therefore, most SWRO desalination plants are designed to work at a higher recovery (45%) (Pique, 2000).

2.5.3 Turbo charger/ Hydraulic Pressure Booster (HPB)

The hydraulic turbocharger is of the centrifugal type and has been in use since 1990s (Peñate, et al., 2011). The turbocharger is used to boost the pressure of the feed that has been pressurized by the HPP to reach the required feed pressure (Grtindisch,et al.,2001).

A turbocharger unit consists of a hydraulic turbine and an HPP. The turbine is similar to a reverse running pump (Farooque et al.,2008). The HPP and turbocharger are not connected directly to overcome the disadvantages that are observed in (FTs) and Pelton wheels, thereby allowing operation flexibility (Stover, 2006). In addition, turbochargers are easy to install and are significantly energy efficient. An SWRO process employing a turbocharger unit is shown in (Fig. 2.8).

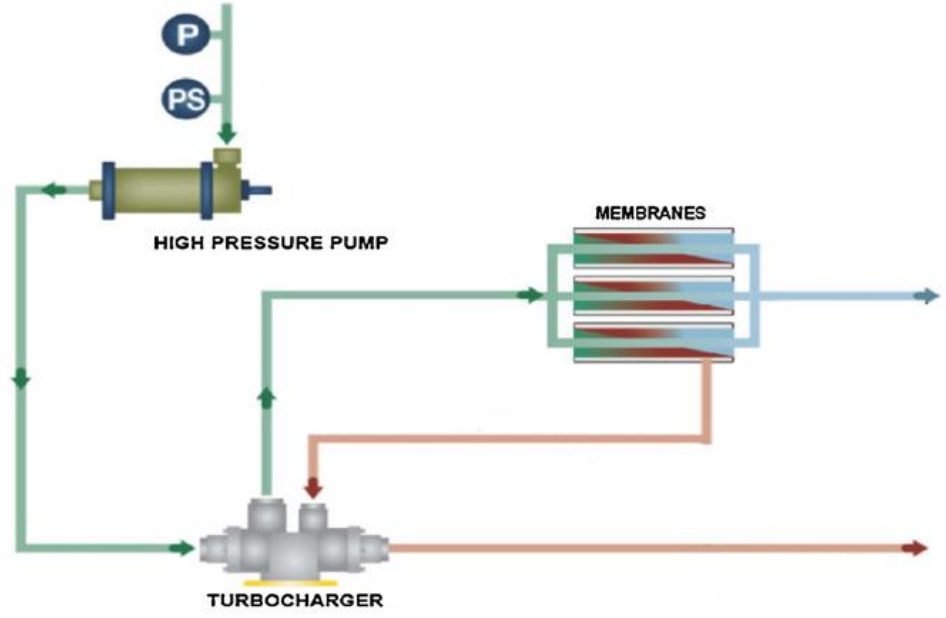


Fig 2.8: A Turbo Charger Unit (El-Ghonemy, 2012)

Both the impeller and the turbine of the turbocharger are centrifugal "close-coupled mixed-type" with both axial and radial flows (Stover, 2006). The maximum efficiency achieved by these devices is (89-90%) (Peñate, 2011), which is slightly higher than the efficiency of the Pelton wheel. The highest transfer efficiency that can be achieved by hydraulic turbocharger is calculated by multiplying the efficiency of impellers, nozzles and turbine, as [90% X 90% X 99%] = 80% (Stover, 2006). Each of these three factors influences the efficiency of this device. The control valves and nozzles can help in adjusting the performance.

2.5.4 Recuperator

The Recuperator designed by Aqualyng^{TM} works on the principle of work exchange. It transfers the hydraulic energy of the brine directly to the hydraulic energy of the feed (Harris, 1999). It is also an Isobaric Energy Recovery Device, especially belonging to the "piston-type" of work exchangers. This device, which belongs to the class of hydraulically driven pumping- in parallel, utilizes buffer separating feed or reciprocating pistons.

The construction of the Recuperator is such that it has vertical stainless steel chambers operating alternatively. They are functioning in a compression-transfer and decompression-discharge sequence. The feed is pre-treated and is pressurized up to a constantly maintained pressure. The flow rate of the feed is also maintained at a constant value.

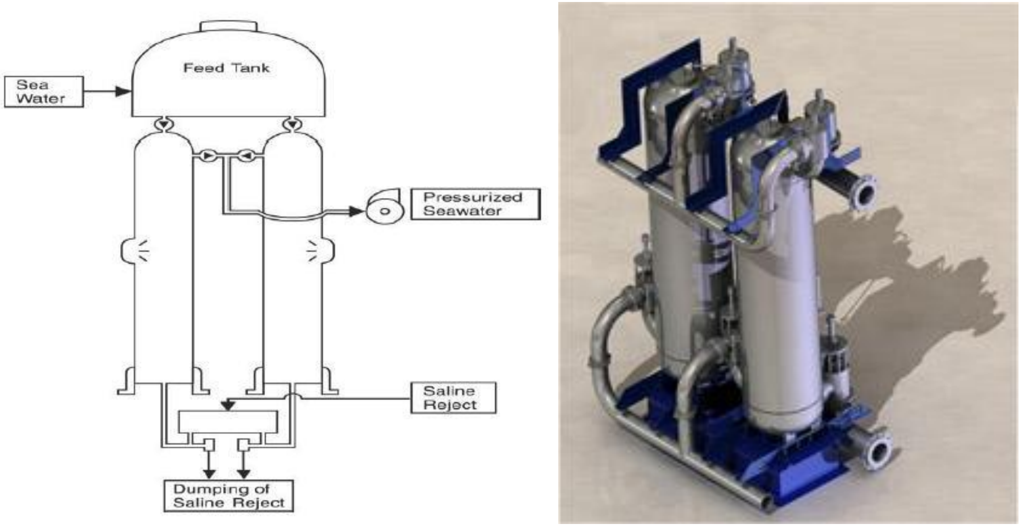


Fig 2.9: Aqualyng^{TM} Pressure Recuperator (Guirguis,2011)

The energy from the pressurized brine is recycled. The device has three-way valves that are specially used to control the flow to the booster pump (LyngAgua, 2001).

2.5.5 Dual Work Exchanger Energy Recovery (DWEER)

The DWEER^{TM} has three main subassemblies: LinXTM valve, the pressure vessel and the check valve nest (Schneider, 2005). A booster pump is also required to boost the feed pressure to make it equal to the pressure of the feed pump (Farooque et al.,2008).

For prevention of mixing, the DWEER^{TM} employs a piston that prevents intermixing of the feed and the brine, and salinity is also kept in check (Schneider,2005).

Fig 2.10: DWEER ^{TM} system of the Ashkelon seawater plant (Goichon, 2007)

Since the work exchanger directly transfers energy from the concentrate to the feed, it has higher efficiency in comparison to the Pelton wheel and turbocharger. However, the work exchanger is limited in size, and, although adding units in parallel can increase capacity, the capital cost is high for large plants. And has a large number of moving parts that can be subject to wear.

In case of a work exchanger, losses are more worth considering than efficiency (Flowserve 2009).In contrast to ERDs such as Pelton wheels or (FTs), it is not possible to assess the shaft power in the DWEER^{TM}, while the evaluation of only hydraulic power is also not enough. For this reason, other possible causes of losses are to be considered, which include "Mixing, leakage (lubrication flow), over flush (brine drain), high pressure differential (between reject inlet & feed outlet), low pressure differential (between feed inlet & reject outlet)" (Schneider, 2005).

2.5.6 Pressure Exchanger (PX)

The Pressure Exchanger (PX) is a ceramic pump takes energy from high-pressure brine and recycles it to incoming seawater at over 95% efficiency, which reduces energy requirements to less than 50% of the amount prevalent a few years ago. A pressure exchanger, typically allows recovery and reuse of over 30 % of the total initial energy applied for salt separation.

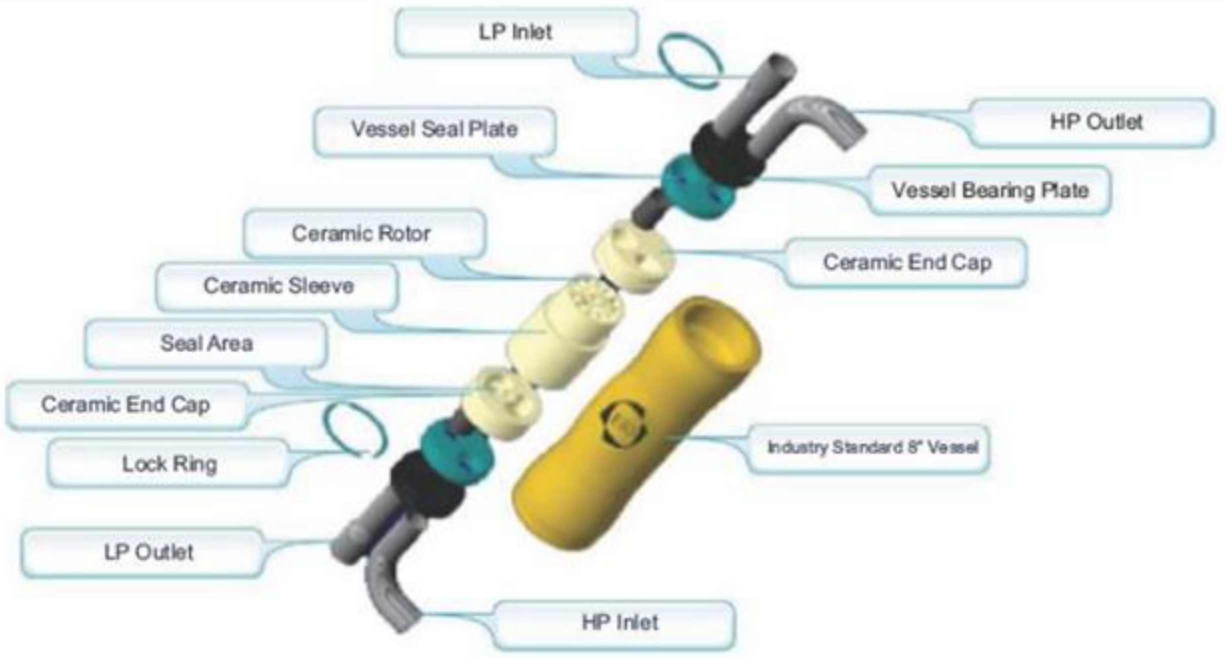


Fig 2.11: Exploded View of ERI Pressure Exchanger (Guirguis,2011)

The (PX) is a new isobaric energy recovery device utilizes the principle of positive displacement to transfers the energy from the concentrate (reject) stream directly to the feed stream in a cylindrical rotor with longitudinal ducts. The rotor spins inside a sleeve between two end covers that divide the rotor into high and low pressure halves. The low-pressure side of the rotor fills with seawater while the high-pressure side discharges seawater. The rotation simply facilitates the valving mechanism, which is to transport the ducts from one side to the other.

The units that operate with direct contact of concentrate and feed experience some mixing, which results in an increased feed salinity, in the range of 3%.

Applying (PX) pressure exchanger technology to SWRO is different from conventional energy recovery device system design, but in practice is quite simple. The reject brine from the SWRO membranes is passed into the (PX) unit, where its pressure energy is transferred directly to a portion of the incoming raw seawater at up to 97% efficiency. This seawater stream, nearly equal in volume and pressure to the reject stream, then passes through a high-pressure booster pump, not the main high-pressure pump. This booster pump is making up the pressure losses across the RO membrane (approx. 2 bar), (PX) unit(s) (approx. 1 bar) and piping losses (approx. 0.5 bar), the total head provided by the booster pump is typically around 3.5 bars.

It is important to notice that the (PX) and associated booster pump are handling nearly 100% of the reject flow. The size of the main high-pressure pump has been reduced to a “make up pump” for the permeate flow that is exiting the RO system. Product water flow and reject flow are being two provided by independent pumping systems and therefore are independent of one another.

The Work exchanger devices that are built for seawater RO plants are treated as the most noteworthy technological breakthrough in desalination techniques achieved in the last 15 years. These devices are not as similar devices used in lesser demanding environments; (PX) is able to meet the tough requirement as it is specially built for SWRO systems. Subsequently, (PX) design has seen many improvements, which have resulted in higher capacity of the single rotor to a very high value of 50 m^3/ hr (MacHarg, 2002).

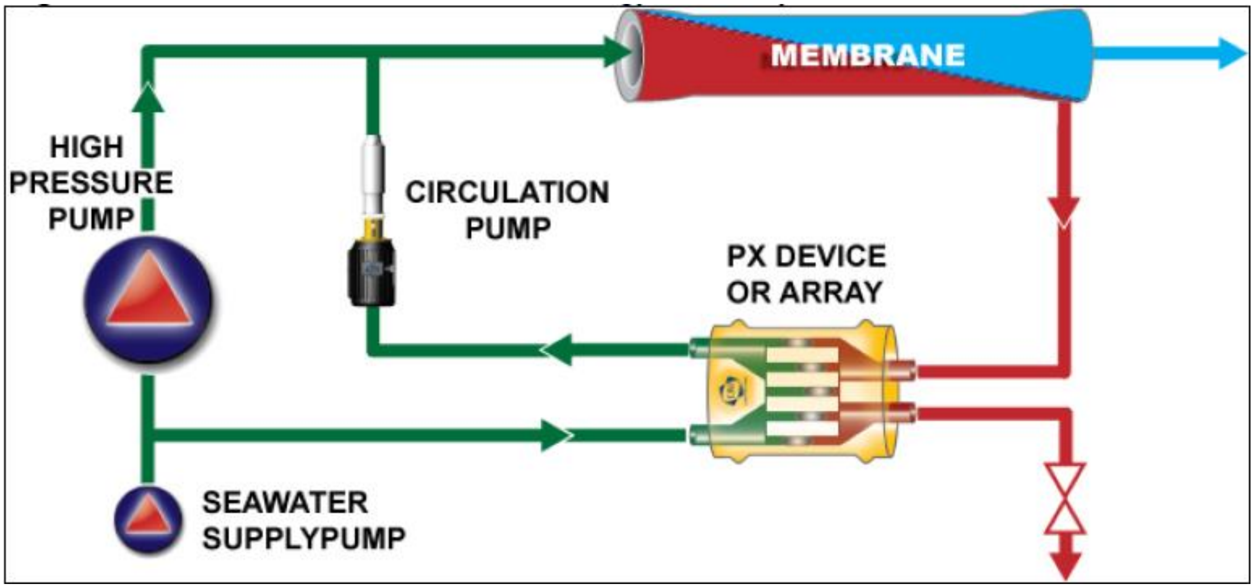


Fig 2.12: ERI’s PX Pressure Exchanger®. (Stover R.L, 2007)

More than 400 seawater reverse osmosis (SWRO) units all over the world have employed ERI’s (PX) Pressure Exchanger® ERDs. Just in the year 2006, more than 2500 units were supplied which are having a combined capacity of 1.8 million m^3/ day of the permeate fluid (Cameron, et al., 2008).Many of these plants have a capacity of 100,000 m^3/ day and there many bigger plants too. For example Perth, Australia has a unit of 160,000 m^3/ day, Hamma in Algeria has installed a unit of 200,000 m^3/ day, Hadera in Israel has installed a plant of 274,000 m^3/ day (Membrane Technology, 2008(9)).

Fig 2.13: PX Device Array Serving SWRO Train 6A Perth, Australia (Sanz and Stover, 2007).

CHAPTER 3

CASE STUDY

3.1 Introduction

The 143,000 cubic meters per day seawater desalination plant in Kwinana Beach (Perth), Western Australia started up in November 2006. As of February 2007, it was the largest SWRO desalination plant in the Southern Hemisphere and the third largest SWRO plant in the world. The plant was built as a joint venture of Suez Degrémont and Multiplex Engineering Pty Ltd. It is operated by Australian Water Services, a subsidiary company of Degrémont (Sanz and Stover, 2007).The aim was to increase drinking water production capacity for Perth, where conventional freshwater resources are in very short supply.

The energy consumption of the first pass SWRO train is approximately 2.5 kilowatt hours per cubic meter (Sanz and Stover, 2007).

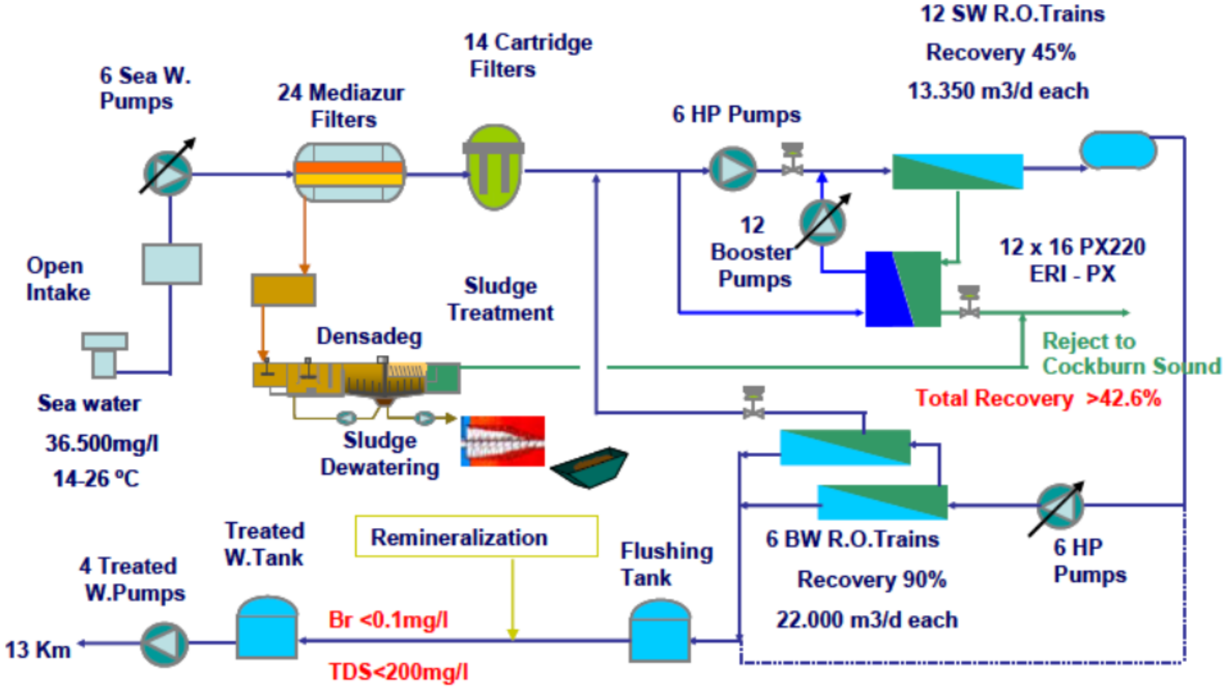


Fig 3.1: Perth seawater desalination plant process diagram. (Richard and Crisp 2008)

3.2 Process Description

The Perth plant draws feedwater from an open intake in nearby Cockburn Sound. The water temperature ranges from (18 to 23 °C) and the salinity is 36,000 to 37,000 ppm.Six supply pumps draw through screens and discharge to dual media filter vessels which in turn discharge through cartridge filters to the reverse osmosis process. The supply pumps are controlled by variable frequency drivers (VFDs) to save energy and assure constant feed pressure to the high-pressure pumps and energy recovery devices.

In Pretreatment process after screening and pumping, acidification with $H2SO_4$ then coagulation with $FeCl_3$ and organic coagulant aid.

Two banks of twelve pressure dual media filters (anthracite and sand) for a total seawater flow rate up to 14,800 m^3/h.

Two banks of seven cartridge filters each fitted with 360 cartridges (5 microns). All operating parameters fully controlled by means of pressure and flow control loops to automatically compensate temperature fluctuations and membrane permeability and to optimize the energy consumption.

Table 3.1 Perth Project Facts (Gary Crisp,2008)

Total 1st Pass Capacity (PX's installed)	160,000 m^3/day
Permeate Capacity	144,000 m^3/day
SWRO Train Capacity	13,500 m^3/day
Number of SWRO Trains	12
Membrane Water Recovery Rate	43%
SWRO Energy Consumption	2.32 kWh/m^3
Total Plant Energy Consumption	3.2–3.5 kWh/m^3
Efficiency	96.7%

3.3 Design Characteristics of SWRO Desalination Perth Plant

Table 3.2 Design Characteristics of Perth Plant (Sanz and Stover,2007)

Reverse Osmosis	
Number of SWRO Trains in first pass	12
Number of pressure vessel in first pass	162
Pressure Vessel Model	Protec™ 7M side-port
Number of membrane elements in each train	1,134
Membrane element Model	Film^{TM} SW30HR-LE400
Number of BWRO Trains in second pass	6
Number of pressure vessel in second pass	124
Pumping System	
Type of high Pressure Pump	Weir Split-Case Centrifugal Pump
Pump Capacity	1,144 m^3/hr
Pump's Differential Head	620m
Pump's Best Efficiency Point	86%
Number of high pressure Pump in first pass	6 units
Driver Motor capacity	2,600 KW
Energy Recovery Device	
Type of energy recovery device	Pressure Exchanger, PX
Pressure Exchanger Model	ERI PX - 220
Number of pressure exchanger array	12
Number of pressure exchanger in each array	16
Array Capacity	800m^3/hr

Fig 3.2: RO unit in Perth, Australia desalination plant (Sanz and Stover, 2007).

CHAPTER 4

MODELING AND OPTIMIZATION SIMULATION

4.1 Introduction

This chapter will focus on the technical modeling and the performance evaluations of SWRO system. Moreover, these optimizations were restrained to a limited number of process configurations in a given context, thus narrowing the optimization pertinence. A special attention will be paid to the flexibility of the RO process synthesis and to the assessment of local context influence (temperature, water resource quality, etc.).

Optimization methodology has thus been developed, which Includes:

1. A database of up-to-date RO membrane models.
2. Performing the systematic generation of all feasible RO process configurations (process layout and operating conditions) with respect to project specifications and local context.
3. Optimizes the RO process configuration.
4. A focus is made on spiral-wound membranes in accordance with actual market trends.

Design Safety Margin Considerations:

- The recommended pump pressure is higher than the feed pressure by 10% of Net Driving Pressure +3 Psi (0.2 bar) for entry loses.
- A safety margin of 10% should be used for system design whenever the fouling rate cannot be predicted.
- A design should include as a contingency a number of elements 10% higher than calculated.
- The feed pressure should be specified as required for the given product flow with 90% of the calculated membrane elements.

4.2 Sizing of the SWRO System

The approximate RO system size (e.g. Number of membrane elements and pressure vessels, etc.) required to produce a quantity of product water can be determined by the following general steps:

1. Selection the membrane type and corresponding model number.
2. Selection the flux rate (l/m^{2}h) according to expected feed water quality.
3. Divide the desired plant capacity by the design flux rate and by membrane element surface area.
4. Divide total number of elements by the number of elements per pressure vessel. Round result up to the nearest integer.
5. Select the appropriate array to achieve the desired recovery percentage. Increase number of pressure vessels if necessary.

Before utilizing the projection software, some hand calculations should be performed. These will provide a basic insight into the results of the projections, and make optimization task of the required design less time consuming.

4.2.1 Preliminary Design

Case Study: Gaza Seawater Desalination Plant (GSWDP)

It is proposed to construct a seawater water RO plant to provide potable water to Gaza strip. The average proposed capacity is 140,000 m^3/day (7,000m^3/hour).

Step 1: Consideration the source (feed) water quality.

The membrane system design depends on the available feed water and its required application. Therefore; the system design information shall be according to the feed water analysis.

1. A) Choosing Seawater open intake with conventional pretreatment with SDI <5.

1. B) Choosing overall feed water concentration in TDS (ppm) or individual (specific) ions.

Table 4.01: Feed water (seawater) composition

Component/Parameter	Specifications/Design Criteria
Feed water	
▪ Design flow rate	16,000 m^3/day
▪ TDS	37,000 mg/l
▪ Temperature	25^o C
▪ Intake type	open intake

Step 2: Permeate Quality

Table 4.02: Feed water (seawater) composition

Seawater Constituents	Concentration (mg/L)	Concentration (meq/L)	Numbers of milligrams per mole	Molar Concentration (m_i) mole / L
Cations				
Calcium	660		40,000	0.0165
Magnesium	1,447		24,300	0.059547325
Sodium	10,200		23,000	0.443478261
Potassium	510		39,100	0.013043478
Boron	4		10,800	0.00037037
Bromide	65			
Total Cations	**12,886**		**–**	**0.532939435**
Anions				
Bicarbonate	160		61,000	0.002622951
Sulfate	2500		96,100	0.026014568
Chloride	21500		35,500	0.605633803
Fluoride	0		19,000	0
Nitrate	0.1		62,000	0
Silica	10			
Total Anions	**24,170.1**		**–**	**0.634272935**
Total	**37,056.1**			**$\sum m_i$ =1.1667**

The required quality of permeate;

Table 4.03: Required quality of permeate

Criteria		Level
Chloride Concentration		70 ppm (Max)
Salinity	TDS	400 ppm (Max)
	Na	60 ppm (Max)
	Boron	0.3 ppm (Max)
Free Chlorine Concentration	0.1 – 0.5 ppm	
pH	7.5 – 8.5 max	
Hardness	> 80 mg/l as $CaCo_3$	
Alkalinity	> 80 mg/l as $CaCo_3$	
Turbidity	< 0.5 NTU max	

Step 3: Selection the flow configuration and number of passes.

The SWRO system is designed for continuous operation and the operating conditions of every membrane element in the plant are constant with time. A permeate staged (partial two passes) system is selected where the second pass is two staged.

Step 4: Calculate the SWRO units required.

This calculation provides the basic RO units capacity. It is important to notice that RO units are classified based on permeate production, not feed water quantity. And a portion of the plant output consists of first pass permeate that has been blended with the final SWRO permeate. The basis for selecting the number of units really depends on local conditions, daily Vs. night-time demand, etc.

Availability and Redundancy of operation of RO system

Availability**:** number of operation hours in a year after reducing the downtime.

Redundancy: spare production ability.

The plant daily capacity = 140,000 m^3/ day.

The plant yearly capacity = 140,000*365 = 51,100,000 m^3/yr.

Number of hours in a year = 365*24 = 8,760 hours.

Plant average flow = $\frac{51,100,000}{8,760} = 5,833\ m^3/hr.$

The number of operation hours in a year are 8, 0000 hours. Where 760 hours are for downtime due to maintenance etc.).

Plant flow with availability factor $= \frac{51,100,000}{8,000} = \quad 6,388\ m^3/hr.$

Plant flow with availability and redundancy factors of 10% = 6,388*1.1= 7,026 m^3/hr.

Usually; each SWRO train is designed to produce (10-20%) of total permeate capacity

So; we select 12 SWRO trains in first Pass, 6 BWRO trains in second pass.

Step 5: Selection the membrane element type.

Elements are selected according to feed water salinity, feed water fouling tendency, required rejection and energy requirements. The standard element size is 8-inch in diameter and 40-inch long.

The membrane type then determined according to:

- Application.
- Feed water characteristics.
- Required permeate quality.
- Operational factors such as energy or chemical consumption.
- Long term operation issues (CIP frequency, membrane life time).

Table 4.04: Choosing the SWRO membrane (ADAN, 2011).

Application	Membrane main characterization	Representative membrane models
Seawater	RO high rejection	DOW - SW 30XHR, DOW - SW 30HRLE Hydranautics – SWC4+5+ESAPAB
	RO low energy	DOW - SW 30XLE, SW 30ULE, Hydranautics – SWC5.
Brackish water	RO high rejection	DOW-BW 30HR, DOW-BW 30, Hydranautics ESPA2,CPA3

Table 4.05: Choosing the SWRO membrane (DOW) (ADAN, 2011).

Membrane type	Membrane main characterization	Permeate flow (m^3/ day)	Salt Rejection (%)	Active Area (m^2)
DOW – SW 30HRLE – 440i	SW – high rejection	31	99.8	41
DOW – SW 30ULE – 440i	SW – Low energy	45.4	99.7	41
DOW – SW 30HRLE – 370/34i	SW-fouling resistant	25.3	99.8	34
DOW –HRLE – 440i	BW – Low energy	48	99.5	41
DOW – BW 30HR – 440i	BW – high rejection	48	99.7	41

I will select different types of membrane elements by using ROSA software to compare their impact & performance with respect to specific energy consumption.

Step 6: Selection the average membrane flux.

Once the SWRO units size have been estimated, the rough number of membrane elements can be calculated based on typical average flux commonly found in operating facilities.

Table 4.06: Selection the design average permeate flux and RO recovery (ADAN, 2011).

No	Feed type	Ave. permeate Flux (l / m^2 * hr)	Max. recovery range
1	Seawater from open intake	10-15	40% - 50%
2	Seawater from beach wells	10-17	40% - 50%
3	Brackish water	20-29	75% - 85%
4	Tape water, low salinity well water.	24-29	80% - 88%

Since we select seawater open intake as a feed type, so the average permeate flux (10-15 l/m^2*hr) and average recovery (40% - 50%) as given in (table 4.06).

Step 7: Calculation the number of needed elements.

Dividing the design permeate flow rate Q_P (m^3/hr) by the design flux f (m^3/m^2*hr) and by the membrane surface area of the selected element S_E (m^2), to obtain the number of membrane elements N_E.

$$N_E = \frac{Q_P}{f * S_E}$$

$$N_E = \frac{7,000}{0.0125 * 40.9} = 13,692 \ elements.$$

Step 8: Calculation the number of pressure vessels and array that are needed.

Once the number of elements required has been obtained, the number of vessels and the vessel array can be estimated.

Divide the number of elements (N_E) by the number of elements per pressure vessel, (N_{EpV}) to obtain the number of pressure vessels,(N_V) round up to the nearest integer.

$$N_v = \frac{N_E}{N_{Epv}}$$

$$N_v = \frac{13{,}692}{7} = 1{,}956 \textit{ pressure vessels}$$

Since we have 12 trains in first SWRO pass, each train contains 163 pressure vessels.

Step 9: Selection the number of stages.

The number of stages defines how many pressure vessels in series the feed will pass through, until it exits the system and is discharged as a concentrate. Every stage consists of a certain number of pressure vessels in parallel. The number of stages is a function of the planned system recovery, the number of elements per vessel, and the feed water quality.

The staging is necessary for keeping the design limits in flow and recovery in system with high number of elements in pressure vessel and high recovery.

The higher the system recovery and the lower the feed water quality, the longer the system will be with more elements in series.

One-stage systems can also be designed for high recoveries if concentrate recycling is used. In seawater systems the recoveries are lower than in brackish water systems. The number of stages depends on recovery as shown in (Table 4.07).

Table 4.07: Number of Stages of SWRO systems (Dow, 2015).

System Recovery (%)	Number of Serial Element Positions	Number of Stages (6-element vessels)	Number of Stages (7-element vessels)	Number of Stages (8-element vessels)
35 - 40	6	1	1	----
45	7 - 12	2	1	1
50	8 - 12	2	2	1
55 - 60	12 - 14	2	2	----

The first SWRO pass will be single stage based on above given table.

Step 10: Selection the staging ratio.

The relation of the number of pressure vessels in subsequent stages is called the staging ratio (R).

The ideal staging of a system is such that each stage operates at the same fraction of the system recovery, provided that all pressure vessels contain the same number of elements. The staging ratio (*R*) of a system with (*n*) stages and a system recovery (*Y*) -as fraction- can then be calculated:

$$R = \left[\frac{1}{(1-y)}\right]^{\frac{1}{n}}$$

For n = 2, y = 90%

$$R = \left[\frac{1}{(1-0.90)}\right]^{\frac{1}{2}} = 3.16$$

The number of pressure vessels in the first stage $N_{v\,(1)}$ can be calculated with the staging ratio *R* from the total number of vessels N_v as following:

For two-stages system (n=2);

$$N_{v\,(1)} = \frac{N_v}{1+R^{-1}} \qquad \text{for n= 2}$$

The total number of pressure vessels (N_v)= 300 Pvs

The staging ratio = 3.16

$$N_{v\,(1)} = \frac{300}{1+3.16^{(-1)}} \quad =228 \qquad \textit{say } 230.$$

The number of vessels in the second stage is then;

$$N_{v\,(2)} = \frac{N_v(1)}{R} \qquad \text{and so on.}$$

$$N_{v\,(2)} = \frac{225}{3.16} \quad =68 \qquad \textit{say } 70.$$

Step 11: Selection of high pressure feed pump.

The horizontal Split Multistage centrifugal Pump with capacities of 2,500-3,000 m^3/hr each and rated efficiency 88%, and 16 booster pumps

Step 12: Selection of energy recovery device.

From ERI ^{TM} PX ^{TM} POWER MODEL; 12 array with 16 pressure exchanger (PX-Q260), each array capacity 690 m^3/hr and efficiency 97.3%.

Step 13: Analysis and optimization the membrane system

The chosen system will be analyzed and refined using the Reverse Osmosis System Analysis (ROSA) computer program.

4.3 Using Projection Tool (Software Design)

Once the preliminary design has been established, the projection software may be used to check the validity of the design, determine the maximum water recovery available, and establish permeate quality and blending potential. Not all software packages contain the subroutines necessary for making the blending calculations, but sufficient information can be obtained from those manufacturers that do provide this feature to allow an estimate for those that do not. The blended water quality provides the basis for determining the post treatment requirements.

Reverse Osmosis System Analysis (ROSA)

The Reverse Osmosis System Analysis (ROSA) model, a sophisticated RO design program that predicts the performance of membranes in user-specified systems.

Model Description

ROSA 9.1 software is the latest version, used in the analysis to determine the performance of a membrane and energy requirements for desalination. The use of the model is influenced by the need to design a technically feasible RO system. The ROSA model has been used for designing desalination plants in different parts of the world.

Dow/Film Tec-ROSA

The RO performance software Reverse Osmosis System Analysis (**ROSA**) can now be used to finalize and optimize the plant design, provide details for selecting a feed pump, and provide information for post treatment requirements.

ROSA program has four input pages, one report page and cost analysis page, each tabbed on the bottom of the screen. The six tabs are:

1. Project Info.
2. Feed Data.
3. Scaling.
4. System Configuration.
5. Cost analysis.
6. Report.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Introduction

The energy required to desalinate with an SWRO system can be expressed in terms of the specific energy consumed per cubic meter of permeate and calculated with the following equivalent equations:

$$SEC = \frac{(E_{HP} + E_{BP} + E_{SP})}{Q_P} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..5.1\ (Stover\ R.L, 2007)$$

$$SEC = \frac{\left[\frac{Q_{HP}(P_{HP} - P_F)}{E_{HP}} + \frac{Q_{BP}(P_{HP} - P_{BPI})}{E_{BP}} + \frac{Q_{SP}(P_F)}{E_{SP}}\right]}{Q_P} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots..5.2\ (Stover\ R.L, 2007)$$

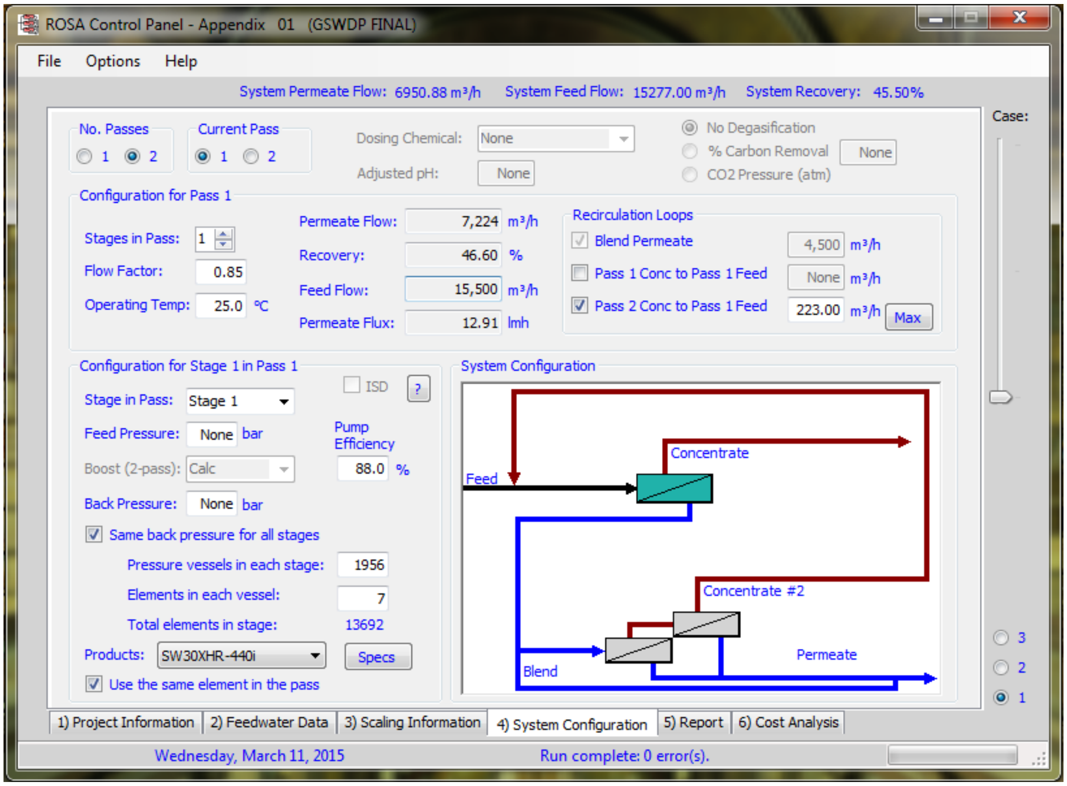
where SEC is the SWRO system specific energy, E_{HP} the high-pressure pump energy consumed, E_{BP} the booster pump energy consumed, E_{SP} the supply pump energy consumed, Q_P the permeate flow rate, Q_{HP} the high-pressure pump flow rate, P_{HP} the high-pressure pump outlet pressure, P_F the high-pressure pump feed water pressure, E_{HP} the high-pressure pump and motor efficiency, Q_{BP} the booster pump flow rate, P_{BPI} the booster pump inlet pressure, E_{BP} the booster pump and motor efficiency, Q_{SP} the booster pump flow rate, and E_{SP} the supply pump and motor efficiency.

5.2 Results and Discussion

The performance of SWRO systems studied and compared with different design configurations equipped with different membrane elements and working under varying operational parameters. In this study three cases have been taken as follows:

5.2.1 CASE 01

Rosa Results



ROSA Control Panel - Appendix 01 (GSWDP FINAL)

System Permeate Flow: 6950.88 m³/h System Feed Flow: 15277.00 m³/h System Recovery: 45.50%

No. Passes ○ 1 ● 2

Current Pass ● 1 ○ 2

Dosing Chemical: None

Adjusted pH: None

● No Degasification

○ % Carbon Removal None

○ CO2 Pressure (atm)

Configuration for Pass 1

Stages in Pass: 1

Flow Factor: 0.85

Operating Temp: 25.0 °C

Permeate Flow: 7,224 m³/h

Recovery: 46.60 %

Feed Flow: 15,500 m³/h

Permeate Flux: 12.91 lmh

Recirculation Loops

☑ Blend Permeate 4,500 m³/h

☐ Pass 1 Conc to Pass 1 Feed None m³/h

☑ Pass 2 Conc to Pass 1 Feed 223.00 m³/h

Configuration for Stage 1 in Pass 1

☐ ISD

Stage in Pass: Stage 1

Feed Pressure: None bar

Pump Efficiency 88.0 %

Boost (2-pass): Calc

Back Pressure: None bar

☑ Same back pressure for all stages

Pressure vessels in each stage: 1956

Elements in each vessel: 7

Total elements in stage: 13692

Products: SW30XHR-440i

☑ Use the same element in the pass

System Configuration

Case: ○ 3 ○ 2 ● 1

Wednesday, March 11, 2015 Run complete: 0 error(s).

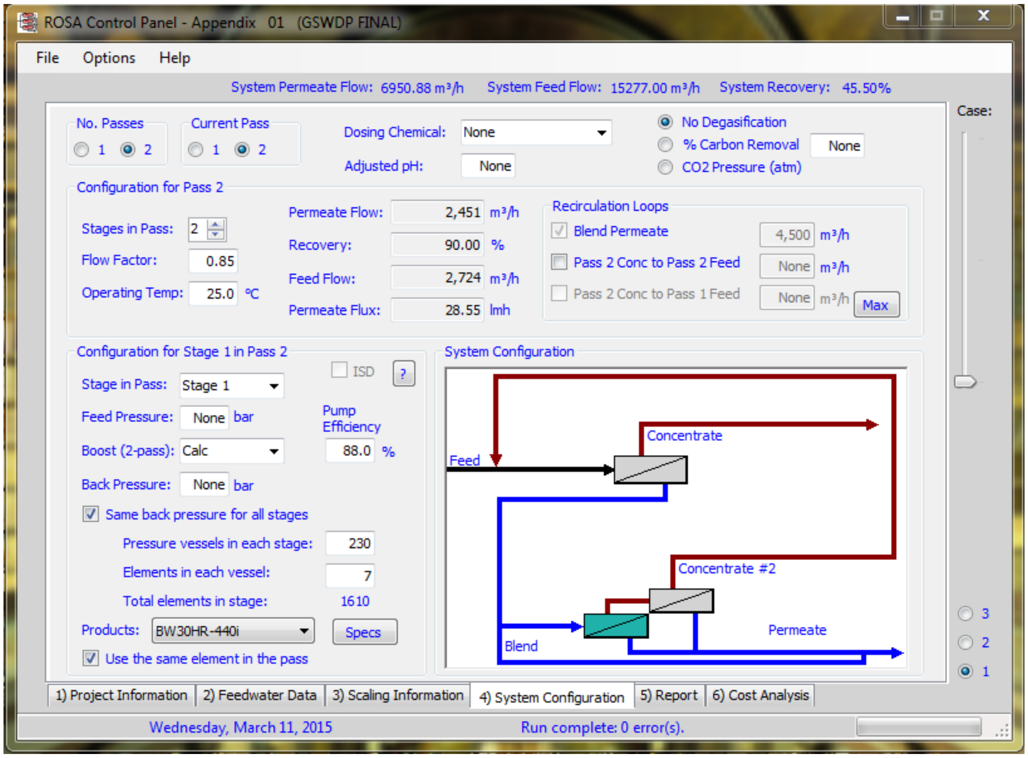
Fig 5.1: System configuration of first pass (case 01)

The figure 5.1 shows the system configuration, in case 01 there are 13692 membrane elements in 1956 pressure vessels where each vessel consists of 7 elements in first stage in first pass, the membrane element type is SW30XHR-440i (Active area = 40.9m^2, flow rate 25m^3/day), with flow factor 0.85.

The Figure 5.2 and Figure 5.3 show the system configuration in second pass consists of 300 pressure vessels each contains 7 elements type BW30HR-440i (Active area=40.9m^2, flow rate 48m^3/day).

4500m^3/hour of first pass permeate is blended with permeate second pass to reach final permeate of 6950 m^3/hour as shown in figure 5.1 and figure 5.4.

The figure 5.4 show the system flow calculated based on pass 1 feed flow, therefore; the feed in pass 1 assumed to be 15500m^3/hour at recovery 46.60%, in pass 2 the recovery set to be 90%, the overall system recovery become 45.50% with final permeate flow 6950m^3/hour.(for more details see Appendix –A).


ROSA Control Panel - Appendix 01 (GSWDP FINAL)

System Permeate Flow: 6950.88 m³/h System Feed Flow: 15277.00 m³/h System Recovery: 45.50%

No. Passes: ○ 1 ● 2
Current Pass: ○ 1 ● 2
Dosing Chemical: None
Adjusted pH: None
● No Degasification
○ % Carbon Removal None
○ CO2 Pressure (atm)

Configuration for Pass 2
Stages in Pass: 2
Flow Factor: 0.85
Operating Temp: 25.0 °C
Permeate Flow: 2,451 m³/h
Recovery: 90.00 %
Feed Flow: 2,724 m³/h
Permeate Flux: 28.55 lmh

Recirculation Loops
☑ Blend Permeate 4,500 m³/h
☐ Pass 2 Conc to Pass 2 Feed None m³/h
☐ Pass 2 Conc to Pass 1 Feed None m³/h

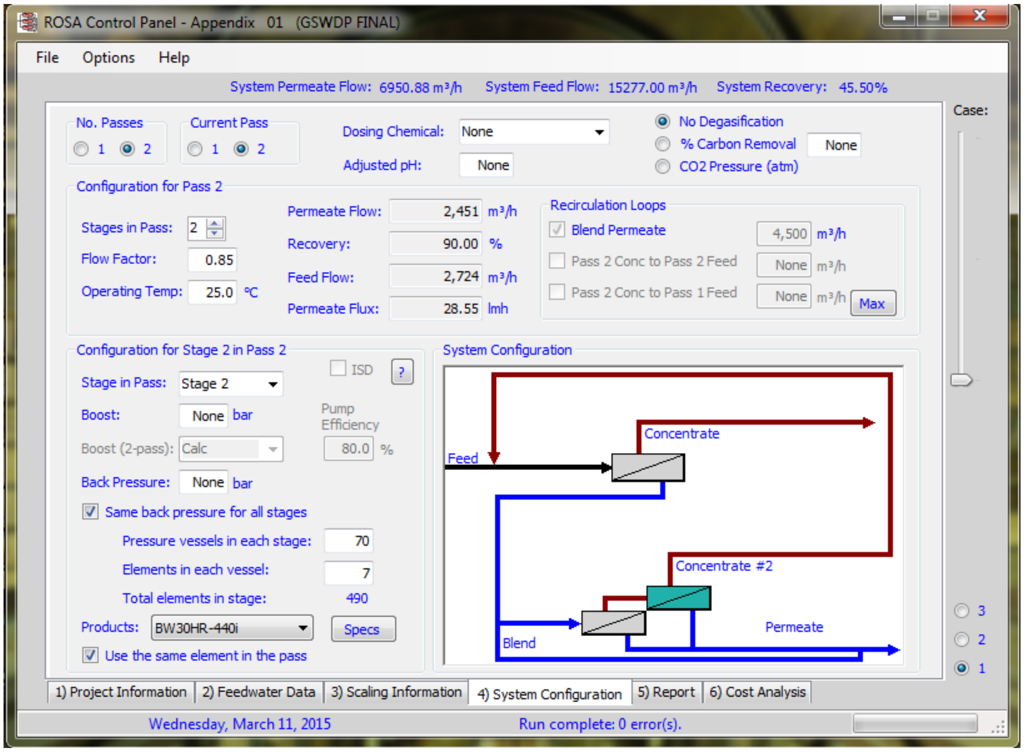
Configuration for Stage 1 in Pass 2
☐ ISD
Stage in Pass: Stage 1
Feed Pressure: None bar
Boost (2-pass): Calc
Pump Efficiency 88.0 %
Back Pressure: None bar
☑ Same back pressure for all stages
Pressure vessels in each stage: 230
Elements in each vessel: 7
Total elements in stage: 1610
Products: BW30HR-440i
☑ Use the same element in the pass

Case: ○ 3 ○ 2 ● 1

Wednesday, March 11, 2015 Run complete: 0 error(s).

Fig 5.2: System configuration of first stage in the second pass (case 01)

The energy consumption of the system is 4.07 Kwh/m^3 in pass 1 and 0.15 Kwh/m^3 in pass 2, as shown in figure 5.5.



System Permeate Flow: 6950.88 m³/h System Feed Flow: 15277.00 m³/h System Recovery: 45.50%

No. Passes: ○ 1 ● 2

Current Pass: ○ 1 ● 2

Dosing Chemical: None

Adjusted pH: None

● No Degasification

○ % Carbon Removal None

○ CO2 Pressure (atm)

Case: ○ 3 ○ 2 ● 1

Configuration for Pass 2

Stages in Pass: 2

Flow Factor: 0.85

Operating Temp: 25.0 °C

Permeate Flow: 2,451 m³/h

Recovery: 90.00 %

Feed Flow: 2,724 m³/h

Permeate Flux: 28.55 lmh

Recirculation Loops

☑ Blend Permeate 4,500 m³/h

☐ Pass 2 Conc to Pass 2 Feed None m³/h

☐ Pass 2 Conc to Pass 1 Feed None m³/h

Configuration for Stage 2 in Pass 2

Stage in Pass: Stage 2

☐ ISD

Boost: None bar

Pump Efficiency 80.0 %

Boost (2-pass): Calc

Back Pressure: None bar

☑ Same back pressure for all stages

Pressure vessels in each stage: 70

Elements in each vessel: 7

Total elements in stage: 490

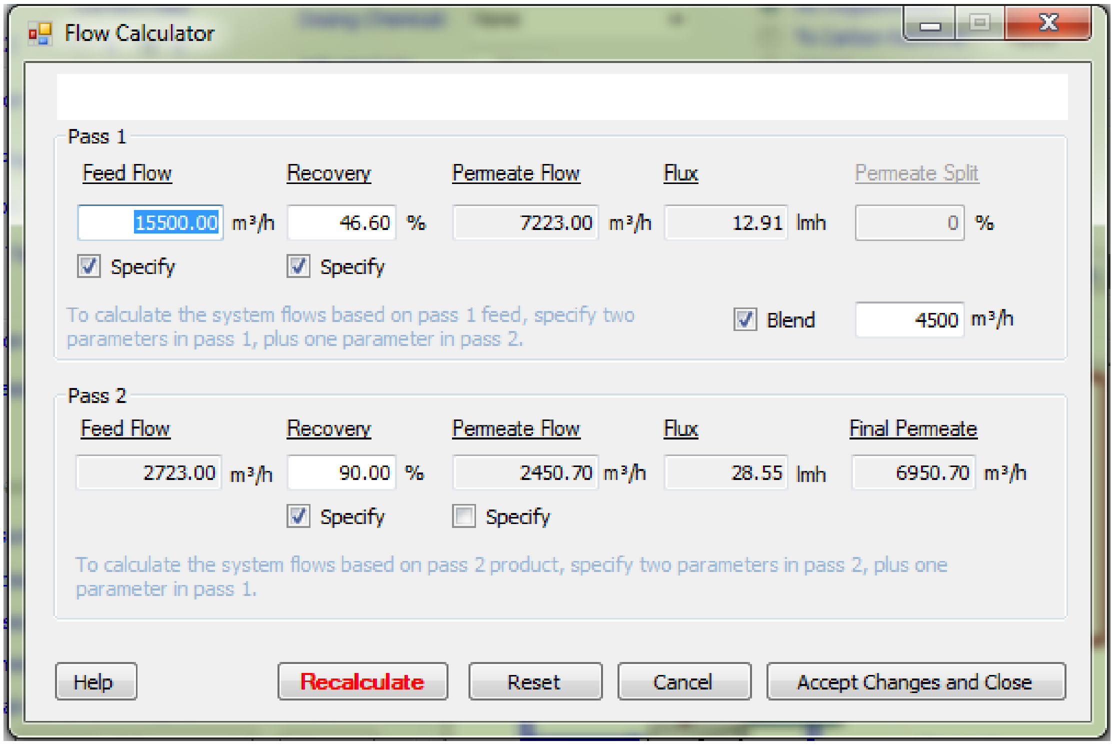
Products: BW30HR-440i

☑ Use the same element in the pass

System Configuration

Wednesday, March 11, 2015 Run complete: 0 error(s).

Fig 5.3: System configuration of second stage in the second pass (case 01)



Pass 1

Feed Flow	Recovery	Permeate Flow	Flux	Permeate Split
15500.00 m³/h	46.60 %	7223.00 m³/h	12.91 lmh	0 %
☑ Specify	☑ Specify			

To calculate the system flows based on pass 1 feed, specify two parameters in pass 1, plus one parameter in pass 2.

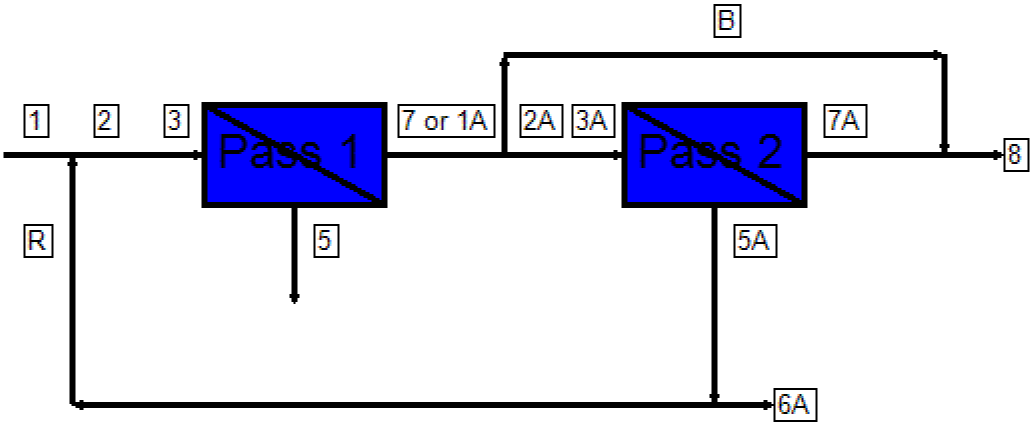
☑ Blend 4500 m³/h

Pass 2

Feed Flow	Recovery	Permeate Flow	Flux	Final Permeate
2723.00 m³/h	90.00 %	2450.70 m³/h	28.55 lmh	6950.70 m³/h
	☑ Specify	☐ Specify		

To calculate the system flows based on pass 2 product, specify two parameters in pass 2, plus one parameter in pass 1.

Fig 5.4: Flow Calculator in first and second pass (case 01)

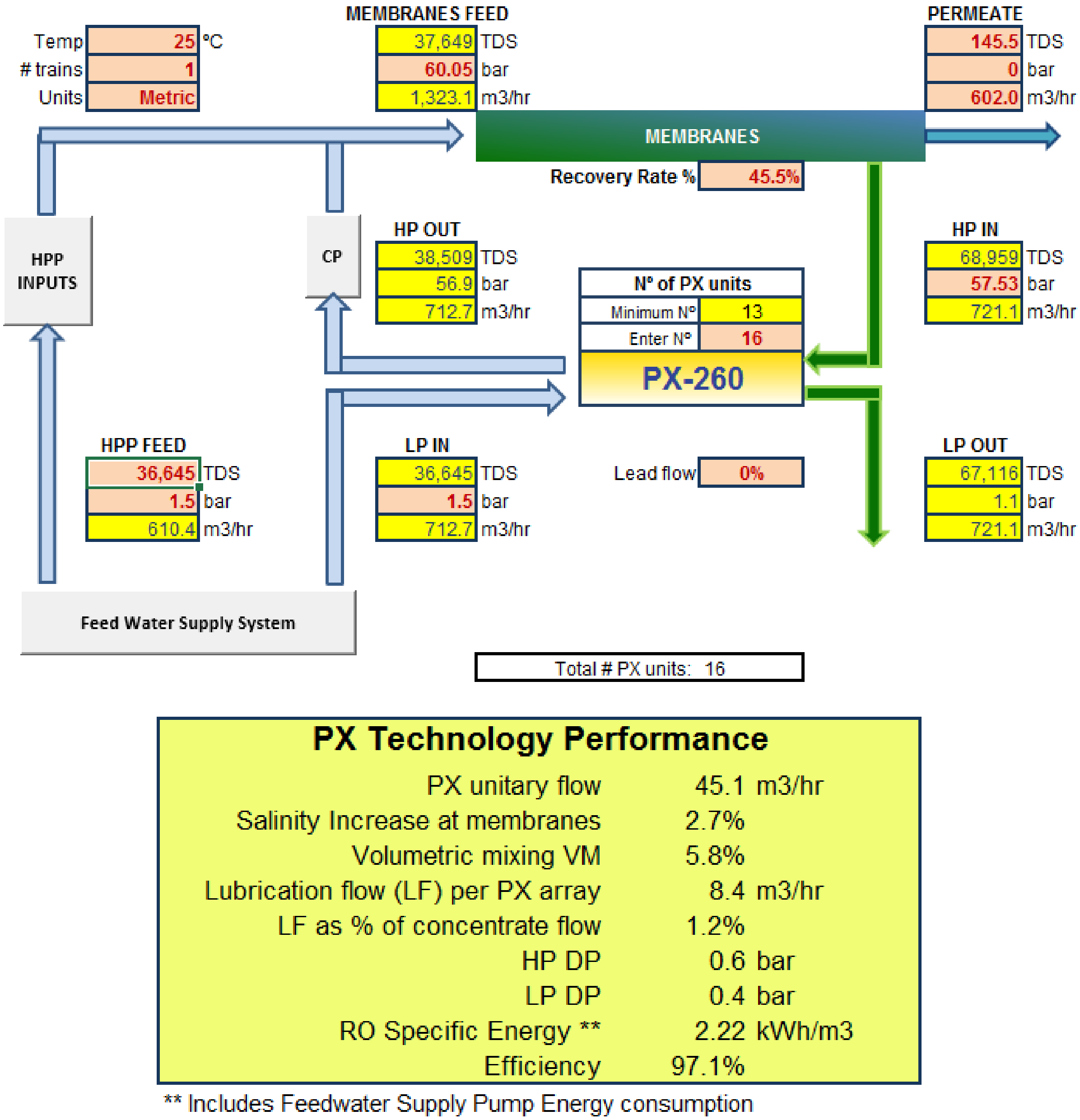


Pass 1				Pass 2			
Stream #	Flow (m³/h)	Pressure (bar)	TDS (mg/l)	Stream #	Flow (m³/h)	Pressure (bar)	TDS (mg/l)
1	15277.00	0.00	36644.64	1A	7224.12	-	145.50
2	15500.00	0.00	36139.47	2A	2724.12	0.00	145.50
3	15500.00	60.05	36139.47	3A	2724.12	12.06	145.50
5	8275.44	57.53	67560.18	5A	273.24	6.31	1410.18
7	7224.12	-	145.50	6A	50.24	6.31	1410.18
7/2	% Recovery	46.61		7A	2450.88	-	4.52
				B	4500.00	0.00	145.50
				R	223.00	6.31	1410.18
				8A	6950.88	0.00	95.78
				7A/2A	% Recovery	89.97	

Pass #	Pass 1	Pass 2	
Stage #	1	1	2
Element Type	SW30XHR-440i	BW30HR-440i	BW30HR-440i
Pressure Vessels per Stage	1956	230	70
Elements per Pressure Vessel	7	7	7
Total Number of Elements	13692	1610	490
Pass Average Flux	12.91 lmh	28.55 lmh	
Stage Average Flux	12.91 lmh	30.86 lmh	20.97 lmh
Permeate Back Pressure	0.00 bar	0.00 bar	0.00 bar
Booster Pressure	0.00 bar	0.00 bar	0.00 bar
Chemical Dose	-	-	
Energy Consumption	4.07 kWh/m³	0.15 kWh/m³	

Fig 5.5: Flow diagram of the process in first and second diagram (case 01)

Energy consumption of the system by using energy recovery



Temp 25 °C
trains 1
Units Metric

MEMBRANES FEED
37,649 TDS
60.05 bar
1,323.1 m3/hr

PERMEATE
145.5 TDS
0 bar
602.0 m3/hr

Recovery Rate % 45.5%

HP OUT
38,509 TDS
56.9 bar
712.7 m3/hr

HP IN
68,959 TDS
57.53 bar
721.1 m3/hr

N° of PX units
Minimum N° 13
Enter N° 16

HPP FEED
36,645 TDS
1.5 bar
610.4 m3/hr

LP IN
36,645 TDS
1.5 bar
712.7 m3/hr

Lead flow 0%

LP OUT
67,116 TDS
1.1 bar
721.1 m3/hr

Total # PX units: 16

PX Technology Performance

PX unitary flow	45.1 m3/hr
Salinity Increase at membranes	2.7%
Volumetric mixing VM	5.8%
Lubrication flow (LF) per PX array	8.4 m3/hr
LF as % of concentrate flow	1.2%
HP DP	0.6 bar
LP DP	0.4 bar
RO Specific Energy **	2.22 kWh/m3
Efficiency	97.1%

** Includes Feedwater Supply Pump Energy consumption

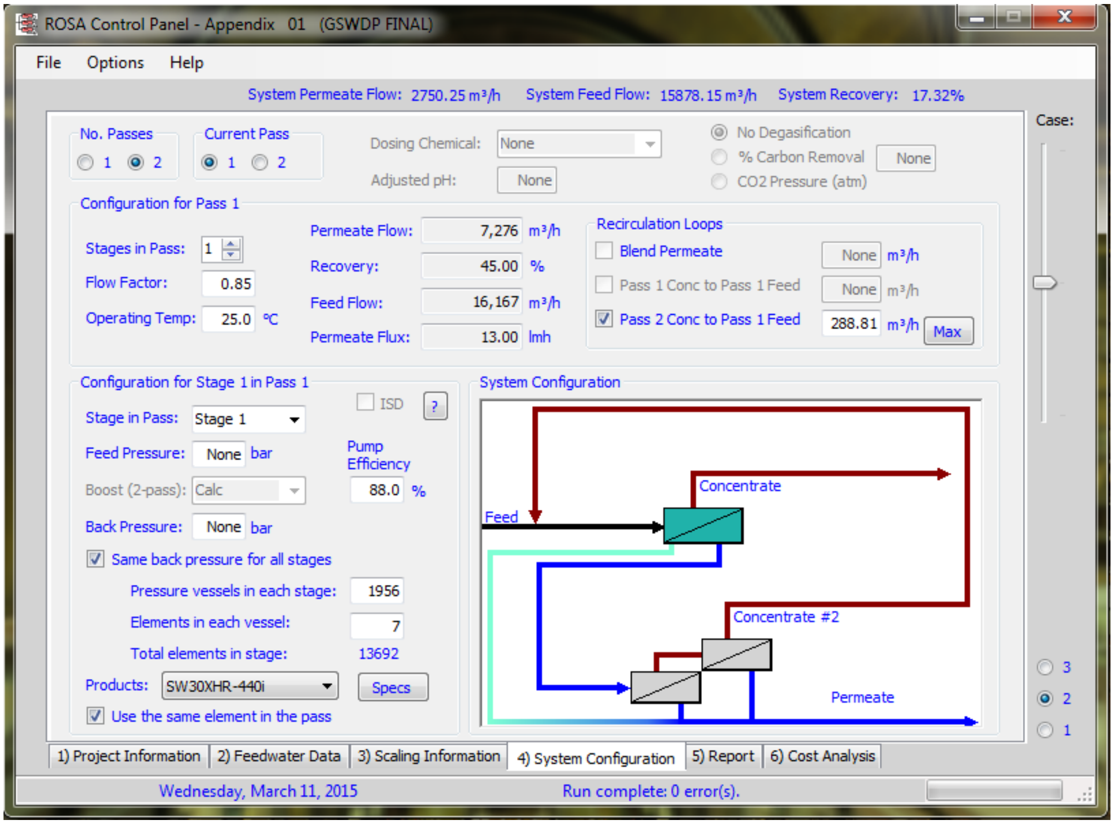
Fig 5.6: ERI^{TM} PX^{TM} power model results (case 01)

The figure 5.6 shows ERI^{TM} PX^{TM} power model modeling outputs with combination of ROSA software such as membrane feed and permeate characteristics and concentrate parameters.

The plant will contains 12 array of pressure exchanger each array has 16 PX-260 units with efficiency 97.1%, flow rate 45.1m^3/hour and volumetric mixing 5.8%, the energy consumption reduced to 2.22Kwh/m^3.

5.2.2 CASE 02

Rosa Results


ROSA Control Panel - Appendix 01 (GSWDP FINAL)

System Permeate Flow: 2750.25 m³/h System Feed Flow: 15878.15 m³/h System Recovery: 17.32%

No. Passes: ○ 1 ● 2
Current Pass: ● 1 ○ 2
Dosing Chemical: None
Adjusted pH: None
● No Degasification
○ % Carbon Removal None
○ CO2 Pressure (atm)

Configuration for Pass 1
Stages in Pass: 1
Flow Factor: 0.85
Operating Temp: 25.0 °C
Permeate Flow: 7,276 m³/h
Recovery: 45.00 %
Feed Flow: 16,167 m³/h
Permeate Flux: 13.00 lmh

Recirculation Loops
☐ Blend Permeate None m³/h
☐ Pass 1 Conc to Pass 1 Feed None m³/h
☑ Pass 2 Conc to Pass 1 Feed 288.81 m³/h

Configuration for Stage 1 in Pass 1
Stage in Pass: Stage 1
☐ ISD
Feed Pressure: None bar
Pump Efficiency 88.0 %
Boost (2-pass): Calc
Back Pressure: None bar
☑ Same back pressure for all stages
Pressure vessels in each stage: 1956
Elements in each vessel: 7
Total elements in stage: 13692
Products: SW30XHR-440i
☑ Use the same element in the pass

Case: ○ 3 ● 2 ○ 1

Wednesday, March 11, 2015 Run complete: 0 error(s).

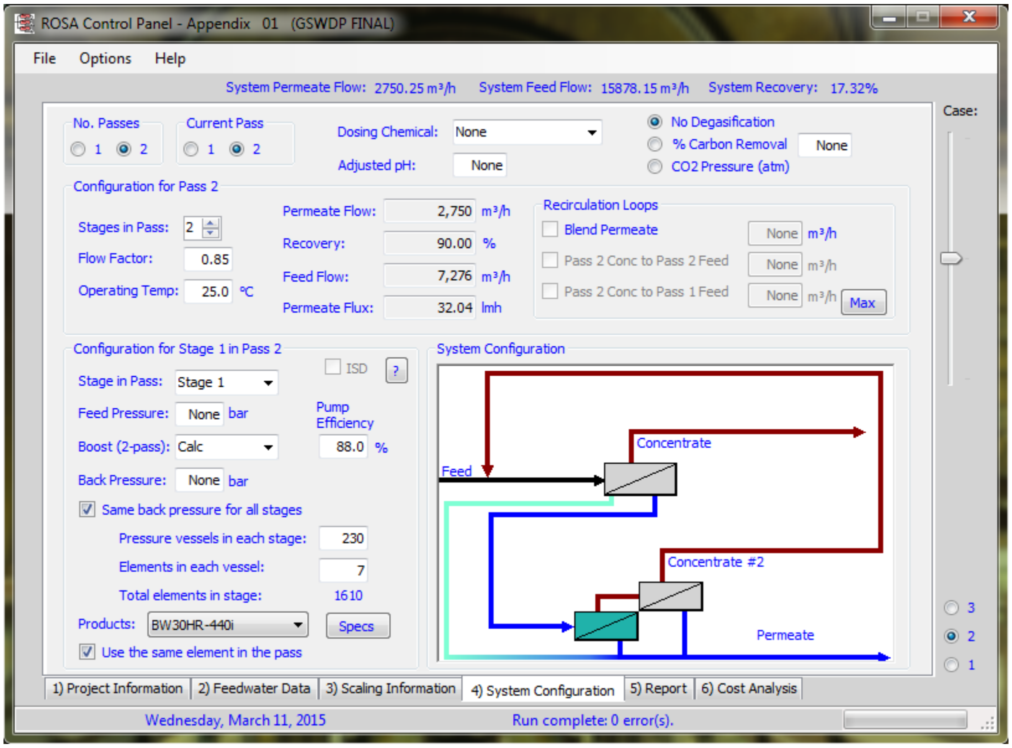
Fig 5.7: System configuration of first pass (case 02)

The figure 5.7 show the system configuration in case 02 consists of 13692 membrane elements in 1956 pressure vessels where each vessel consists of 7 elements in first stage in first pass, the membrane element type is SW30XHR-440i (Active area = 40.9m^2, flow rate 25m^3/day), with flow factor 0.85.

Figure 5.8 and Figure 5.9 show second pass system configuration consists of 300 pressure vessels each contains 7 elements type BW30HR-440i (Active area=40.9m^2, flow rate 48m^3/day).

58% of permeate split in first pass permeate is blended with permeate second pass to reach final permeate of 6970 m^3/hour as shown in figure 5.7 and figure 5.10.

Figure 5.10 show system flow calculation based on pass 2 permeate flow, therefore; the permeate in pass 2 assumed to be 2750m^3/hour at recovery 90.0%, in pass 1 the recovery set to be 45%, the overall system recovery become 43.90% with final permeate flow 6970 m^3/hour.(for more details see Appendix –A).


ROSA Control Panel - Appendix 01 (GSWDP FINAL)

System Permeate Flow: 2750.25 m^3/h System Feed Flow: 15878.15 m^3/h System Recovery: 17.32%

No. Passes ○ 1 ● 2

Current Pass ○ 1 ● 2

Dosing Chemical: None

Adjusted pH: None

● No Degasification

○ % Carbon Removal None

○ CO2 Pressure (atm)

Configuration for Pass 2

Stages in Pass: 2

Flow Factor: 0.85

Operating Temp: 25.0 °C

Permeate Flow: 2,750 m^3/h

Recovery: 90.00 %

Feed Flow: 7,276 m^3/h

Permeate Flux: 32.04 lmh

Recirculation Loops

☐ Blend Permeate None m^3/h

☐ Pass 2 Conc to Pass 2 Feed None m^3/h

☐ Pass 2 Conc to Pass 1 Feed None m^3/h

Configuration for Stage 1 in Pass 2

Stage in Pass: Stage 1

☐ ISD

Feed Pressure: None bar

Pump Efficiency 88.0 %

Boost (2-pass): Calc

Back Pressure: None bar

☑ Same back pressure for all stages

Pressure vessels in each stage: 230

Elements in each vessel: 7

Total elements in stage: 1610

Products: BW30HR-440i

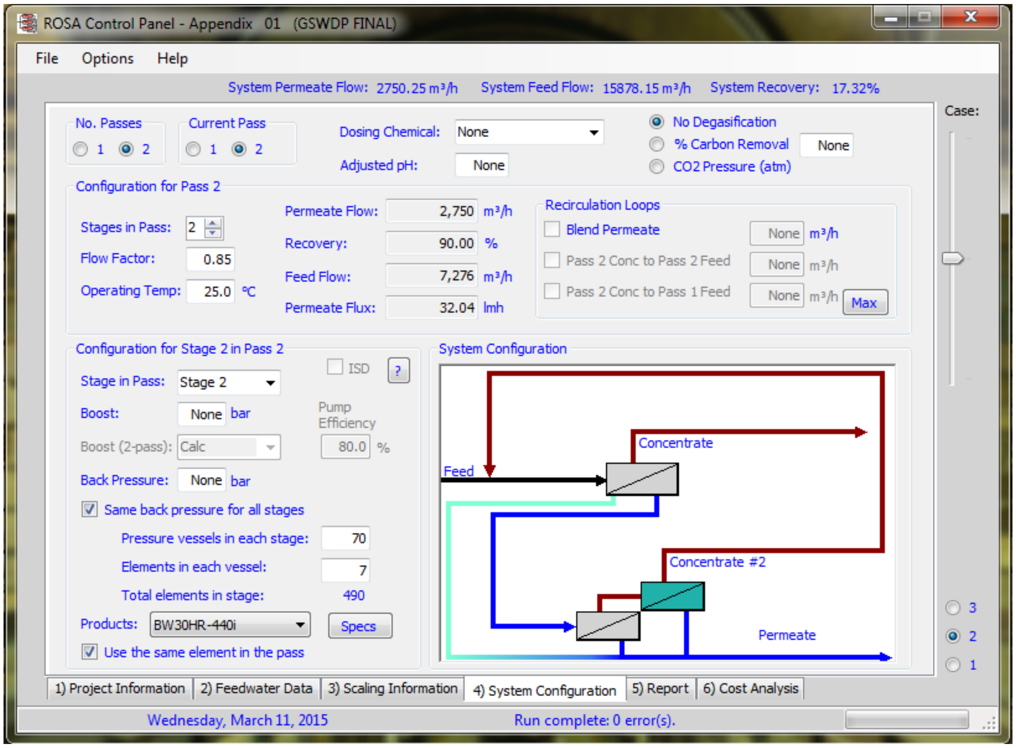
☑ Use the same element in the pass

Case: ○ 3 ● 2 ○ 1

Wednesday, March 11, 2015 Run complete: 0 error(s).

Fig 5.8: System configuration of first stage in the second pass (case 02)

The energy consumption of the system is 4.05 Kwh/m^3 in pass 1 and 0.43 Kwh/m^3 in pass 2, as shown in figure 5.11.


ROSA Control Panel - Appendix 01 (GSWDP FINAL)

System Permeate Flow: 2750.25 m³/h System Feed Flow: 15878.15 m³/h System Recovery: 17.32%

No. Passes: ○ 1 ● 2
Current Pass: ○ 1 ● 2
Dosing Chemical: None
Adjusted pH: None
● No Degasification
○ % Carbon Removal None
○ CO2 Pressure (atm)

Configuration for Pass 2
Stages in Pass: 2
Flow Factor: 0.85
Operating Temp: 25.0 °C
Permeate Flow: 2,750 m³/h
Recovery: 90.00 %
Feed Flow: 7,276 m³/h
Permeate Flux: 32.04 lmh

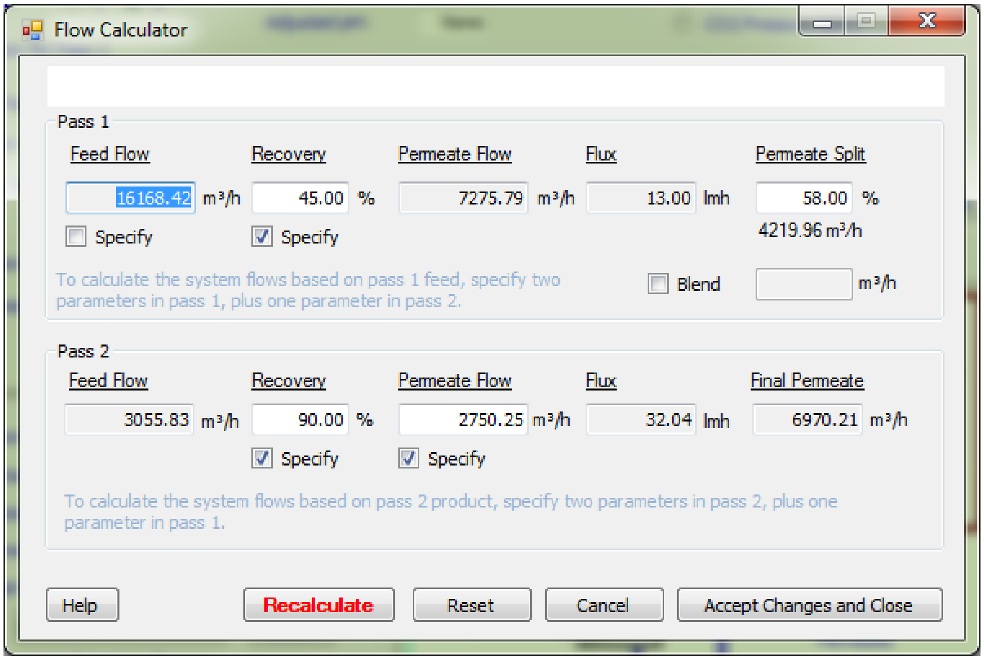
Recirculation Loops
☐ Blend Permeate None m³/h
☐ Pass 2 Conc to Pass 2 Feed None m³/h
☐ Pass 2 Conc to Pass 1 Feed None m³/h

Configuration for Stage 2 in Pass 2
☐ ISD
Stage in Pass: Stage 2
Boost: None bar
Pump Efficiency 80.0 %
Boost (2-pass): Calc
Back Pressure: None bar
☑ Same back pressure for all stages
Pressure vessels in each stage: 70
Elements in each vessel: 7
Total elements in stage: 490
Products: BW30HR-440i
☑ Use the same element in the pass

System Configuration

Wednesday, March 11, 2015 Run complete: 0 error(s).

Fig 5.9: System configuration of second stage in the second pass (case 02)


Flow Calculator

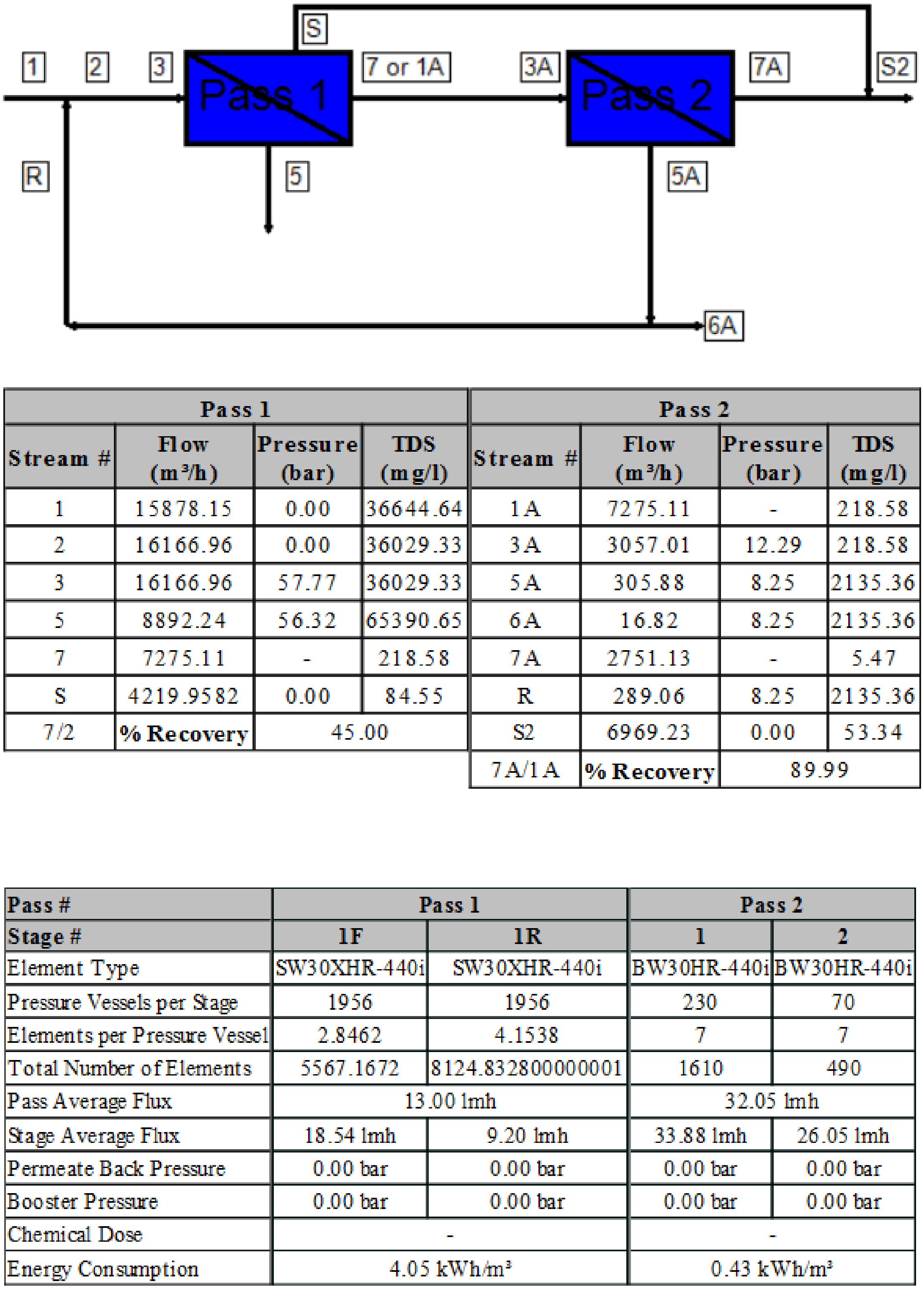
Pass 1
Feed Flow: 16168.42 m³/h ☐ Specify
Recovery: 45.00 % ☑ Specify
Permeate Flow: 7275.79 m³/h
Flux: 13.00 lmh
Permeate Split: 58.00 % 4219.96 m³/h
☐ Blend m³/h

To calculate the system flows based on pass 1 feed, specify two parameters in pass 1, plus one parameter in pass 2.

Pass 2
Feed Flow: 3055.83 m³/h
Recovery: 90.00 % ☑ Specify
Permeate Flow: 2750.25 m³/h ☑ Specify
Flux: 32.04 lmh
Final Permeate: 6970.21 m³/h

To calculate the system flows based on pass 2 product, specify two parameters in pass 2, plus one parameter in pass 1.

Fig 5.10: Flow Calculator in first and second pass (case 02)

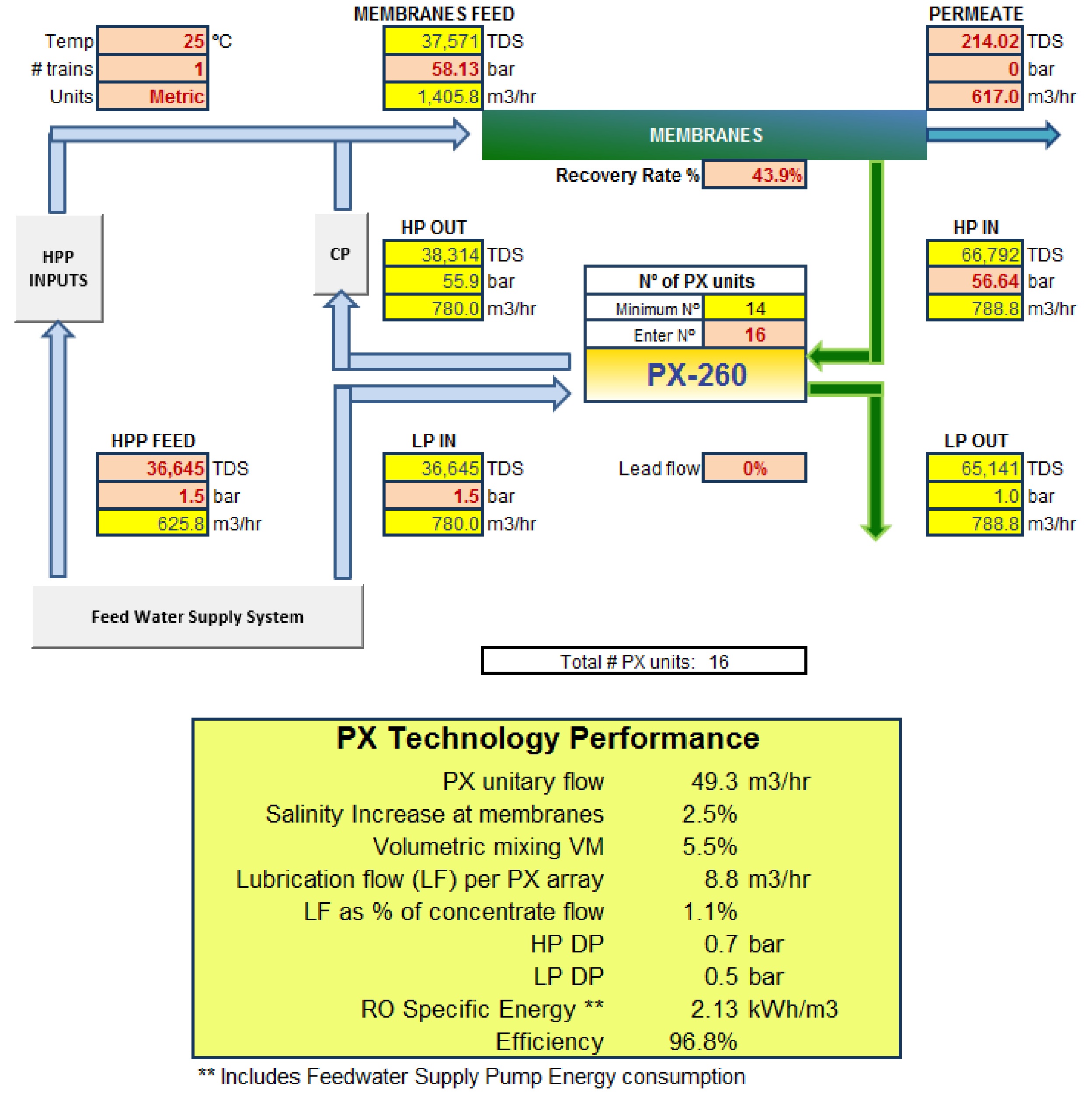


Pass 1				Pass 2			
Stream #	**Flow (m^3/h)**	**Pressure (bar)**	**TDS (mg/l)**	**Stream #**	**Flow (m^3/h)**	**Pressure (bar)**	**TDS (mg/l)**
1	15878.15	0.00	36644.64	1A	7275.11	-	218.58
2	16166.96	0.00	36029.33	3A	3057.01	12.29	218.58
3	16166.96	57.77	36029.33	5A	305.88	8.25	2135.36
5	8892.24	56.32	65390.65	6A	16.82	8.25	2135.36
7	7275.11	-	218.58	7A	2751.13	-	5.47
S	4219.9582	0.00	84.55	R	289.06	8.25	2135.36
7/2	**% Recovery**	45.00		S2	6969.23	0.00	53.34
				7A/1A	**% Recovery**	89.99	

Pass #	**Pass 1**		**Pass 2**	
Stage #	**1F**	**1R**	**1**	**2**
Element Type	SW30XHR-440i	SW30XHR-440i	BW30HR-440i	BW30HR-440i
Pressure Vessels per Stage	1956	1956	230	70
Elements per Pressure Vessel	2.8462	4.1538	7	7
Total Number of Elements	5567.1672	8124.832800000001	1610	490
Pass Average Flux	13.00 lmh		32.05 lmh	
Stage Average Flux	18.54 lmh	9.20 lmh	33.88 lmh	26.05 lmh
Permeate Back Pressure	0.00 bar	0.00 bar	0.00 bar	0.00 bar
Booster Pressure	0.00 bar	0.00 bar	0.00 bar	0.00 bar
Chemical Dose	-		-	
Energy Consumption	4.05 kWh/m^3		0.43 kWh/m^3	

Fig 5.11: Flow diagram of the process in first and second diagram (case 02)

Energy consumption of the system by using energy recovery



Temp 25 °C
trains 1
Units Metric

MEMBRANES FEED
37,571 TDS
58.13 bar
1,405.8 m3/hr

PERMEATE
214.02 TDS
0 bar
617.0 m3/hr

Recovery Rate % 43.9%

HP OUT
38,314 TDS
55.9 bar
780.0 m3/hr

HP IN
66,792 TDS
56.64 bar
788.8 m3/hr

N° of PX units
Minimum N° 14
Enter N° 16
PX-260

HPP FEED
36,645 TDS
1.5 bar
625.8 m3/hr

LP IN
36,645 TDS
1.5 bar
780.0 m3/hr

Lead flow 0%

LP OUT
65,141 TDS
1.0 bar
788.8 m3/hr

Total # PX units: 16

PX Technology Performance

PX unitary flow	49.3 m3/hr
Salinity Increase at membranes	2.5%
Volumetric mixing VM	5.5%
Lubrication flow (LF) per PX array	8.8 m3/hr
LF as % of concentrate flow	1.1%
HP DP	0.7 bar
LP DP	0.5 bar
RO Specific Energy **	2.13 kWh/m3
Efficiency	96.8%

** Includes Feedwater Supply Pump Energy consumption

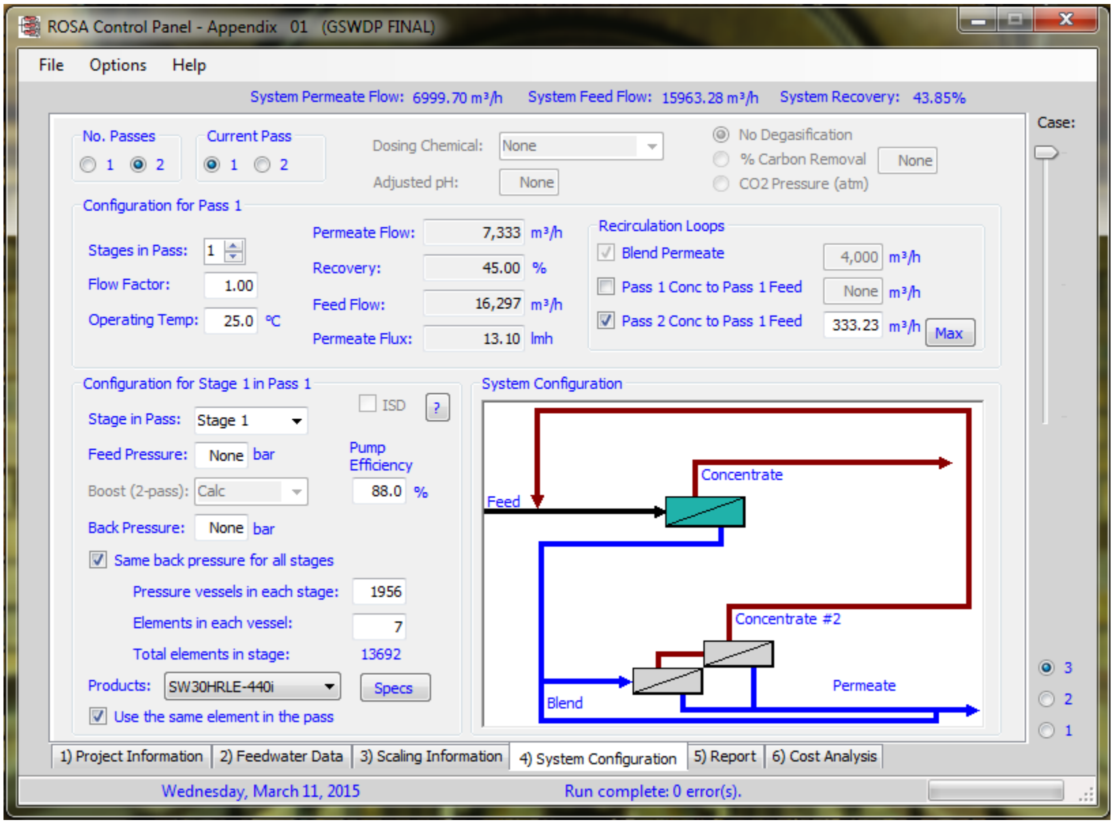
Fig 5.12: ERI^{TM} PX^{TM} power model results (case 02)

The figure 5.12 shows ERI^{TM} PX^{TM} power model modeling outputs with combination of ROSA software such as membrane feed and permeate characteristics and concentrate parameters.

The plant will contains 12 array of pressure exchanger each array has 16 PX-260 units with efficiency 96.8%, flow rate 49.3m^3/hour and volumetric mixing 5.5%, the energy consumption reduced to 2.13Kwh/m^3.

5.2.3 CASE 03

Rosa Results



System Permeate Flow: 6999.70 m³/h System Feed Flow: 15963.28 m³/h System Recovery: 43.85%

No. Passes: ○ 1 ● 2
Current Pass: ● 1 ○ 2
Dosing Chemical: None
Adjusted pH: None
● No Degasification
○ % Carbon Removal: None
○ CO2 Pressure (atm)

Configuration for Pass 1
Stages in Pass: 1
Flow Factor: 1.00
Operating Temp: 25.0 °C
Permeate Flow: 7,333 m³/h
Recovery: 45.00 %
Feed Flow: 16,297 m³/h
Permeate Flux: 13.10 lmh

Recirculation Loops
☑ Blend Permeate: 4,000 m³/h
☐ Pass 1 Conc to Pass 1 Feed: None m³/h
☑ Pass 2 Conc to Pass 1 Feed: 333.23 m³/h

Configuration for Stage 1 in Pass 1
Stage in Pass: Stage 1
☐ ISD
Feed Pressure: None bar
Boost (2-pass): Calc
Pump Efficiency: 88.0 %
Back Pressure: None bar
☑ Same back pressure for all stages
Pressure vessels in each stage: 1956
Elements in each vessel: 7
Total elements in stage: 13692
Products: SW30HRLE-440i
☑ Use the same element in the pass

System Configuration

Case: ● 3 ○ 2 ○ 1

Wednesday, March 11, 2015 Run complete: 0 error(s).

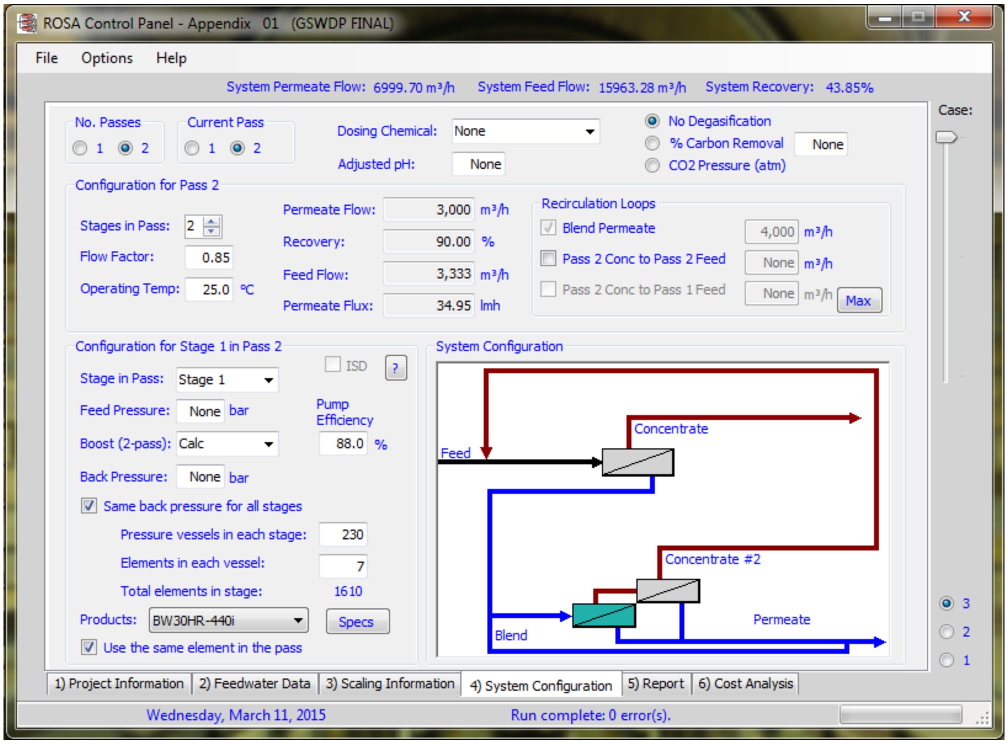
Fig 5.13: System configuration of first pass (case 03)

figure 5.13 shows system configuration in case 03 consists of 13692 membrane elements in 1956 pressure vessels where each vessel consists of 7 elements in first stage in first pass, the membrane element type is SW30HRLE-440i (Active area = 40.9m^2, flow rate 31m^3/day), with flow factor 1.

Figure 5.14 and Figure 5.15 show second pass configuration consists of 300 pressure vessels each contains 7 elements type BW30HR-440i (Active area=40.9m^2, flow rate 48m^3/day).

4000 m^3/hour of permeate in first pass permeate is blended with permeate second pass to reach final permeate of 7000 m^3/hour as shown in figure 5.13 and figure 5.16.

Figure 5.16 shows system flow calculation based on pass 2 permeate flow, therefore; the permeate in pass 2 assumed to be 3000m^3/hour at recovery 90.0%, in pass 1 the recovery set to be 45%, the overall system recovery become 43.85% with final permeate flow 6970 m^3/hour.(for more details see Appendix –A).



System Permeate Flow: 6999.70 m³/h System Feed Flow: 15963.28 m³/h System Recovery: 43.85%

No. Passes ○ 1 ● 2
Current Pass ○ 1 ● 2
Dosing Chemical: None
Adjusted pH: None
● No Degasification
○ % Carbon Removal None
○ CO2 Pressure (atm)

Configuration for Pass 2
Stages in Pass: 2
Flow Factor: 0.85
Operating Temp: 25.0 °C
Permeate Flow: 3,000 m³/h
Recovery: 90.00 %
Feed Flow: 3,333 m³/h
Permeate Flux: 34.95 lmh

Recirculation Loops
☑ Blend Permeate 4,000 m³/h
☐ Pass 2 Conc to Pass 2 Feed None m³/h
☐ Pass 2 Conc to Pass 1 Feed None m³/h

Configuration for Stage 1 in Pass 2
☐ ISD
Stage in Pass: Stage 1
Feed Pressure: None bar
Pump Efficiency 88.0 %
Boost (2-pass): Calc
Back Pressure: None bar
☑ Same back pressure for all stages
Pressure vessels in each stage: 230
Elements in each vessel: 7
Total elements in stage: 1610
Products: BW30HR-440i
☑ Use the same element in the pass

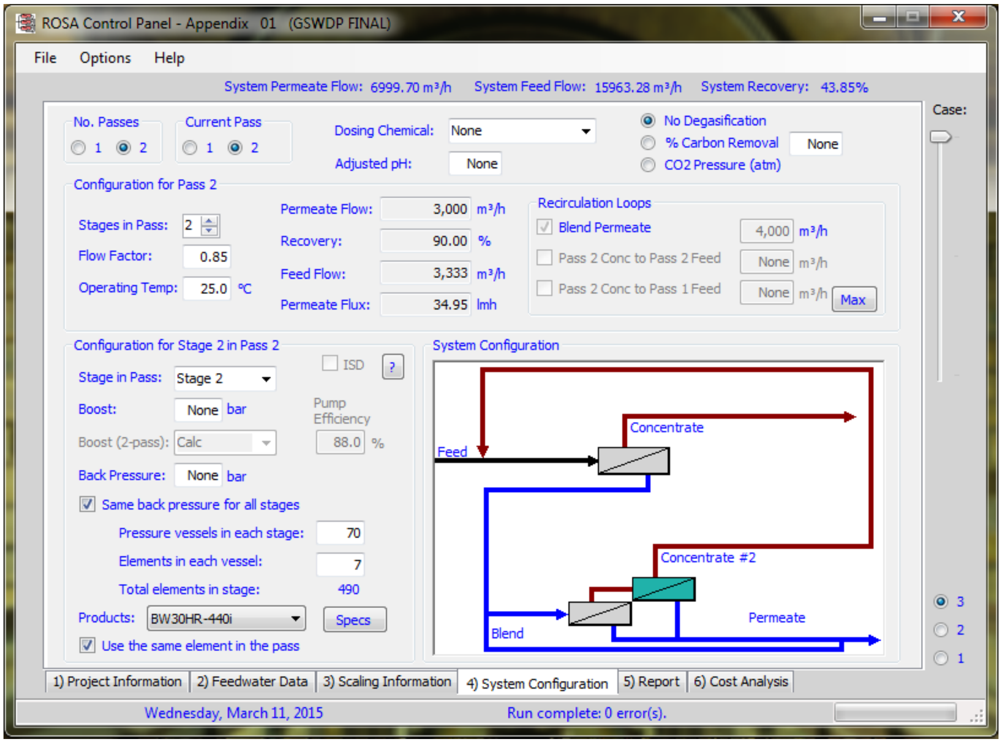
System Configuration

● 3
○ 2
○ 1

Wednesday, March 11, 2015 Run complete: 0 error(s).

Fig 5.14: System configuration of first stage in the second pass (case 03)

The energy consumption of the system is 3.90 Kwh/m^3 in pass 1 and 0.20 Kwh/m^3 in pass 2, as shown in figure 5.17.



System Permeate Flow: 6999.70 m³/h System Feed Flow: 15963.28 m³/h System Recovery: 43.85%

No. Passes: ○ 1 ● 2

Current Pass: ○ 1 ● 2

Dosing Chemical: None

Adjusted pH: None

● No Degasification

○ % Carbon Removal None

○ CO2 Pressure (atm)

Case: ● 3 ○ 2 ○ 1

Configuration for Pass 2

Stages in Pass: 2

Flow Factor: 0.85

Operating Temp: 25.0 °C

Permeate Flow: 3,000 m³/h

Recovery: 90.00 %

Feed Flow: 3,333 m³/h

Permeate Flux: 34.95 lmh

Recirculation Loops

☑ Blend Permeate 4,000 m³/h

☐ Pass 2 Conc to Pass 2 Feed None m³/h

☐ Pass 2 Conc to Pass 1 Feed None m³/h

Configuration for Stage 2 in Pass 2

Stage in Pass: Stage 2

☐ ISD

Boost: None bar

Pump Efficiency 88.0 %

Boost (2-pass): Calc

Back Pressure: None bar

☑ Same back pressure for all stages

Pressure vessels in each stage: 70

Elements in each vessel: 7

Total elements in stage: 490

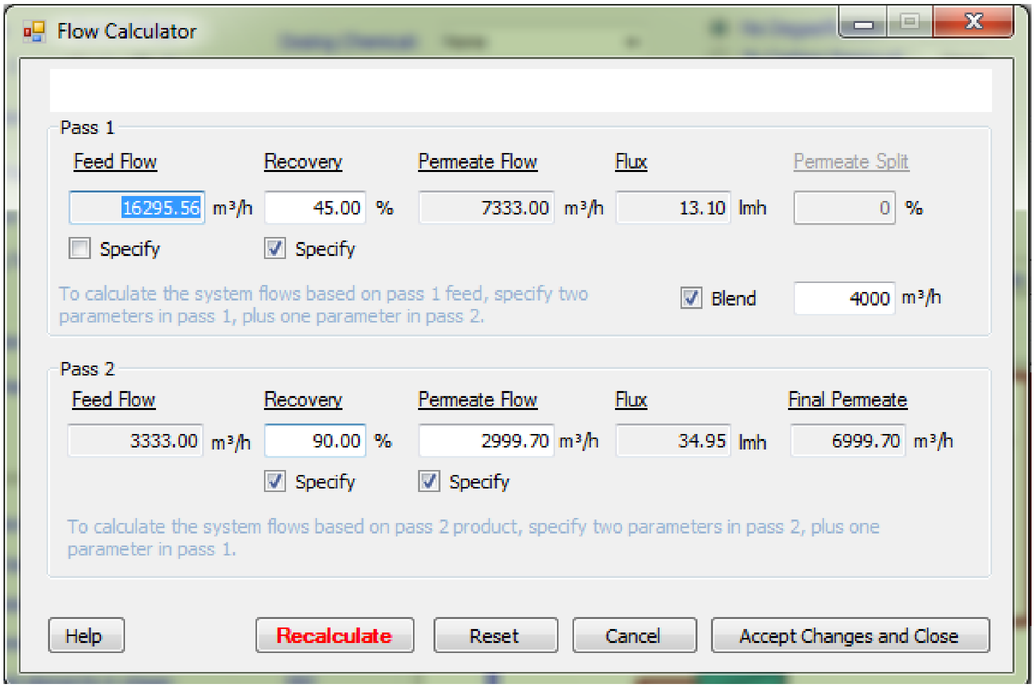
Products: BW30HR-440i

☑ Use the same element in the pass

System Configuration

Wednesday, March 11, 2015 Run complete: 0 error(s).

Fig 5.15: System configuration of second stage in the second pass (case 03)



Pass 1

Feed Flow	Recovery	Permeate Flow	Flux	Permeate Split
16295.56 m³/h	45.00 %	7333.00 m³/h	13.10 lmh	0 %
☐ Specify	☑ Specify			

To calculate the system flows based on pass 1 feed, specify two parameters in pass 1, plus one parameter in pass 2.

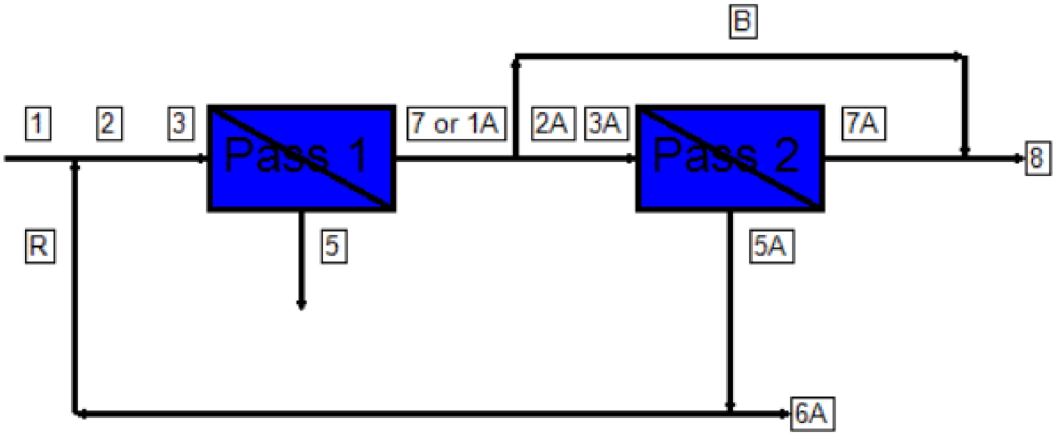
☑ Blend 4000 m³/h

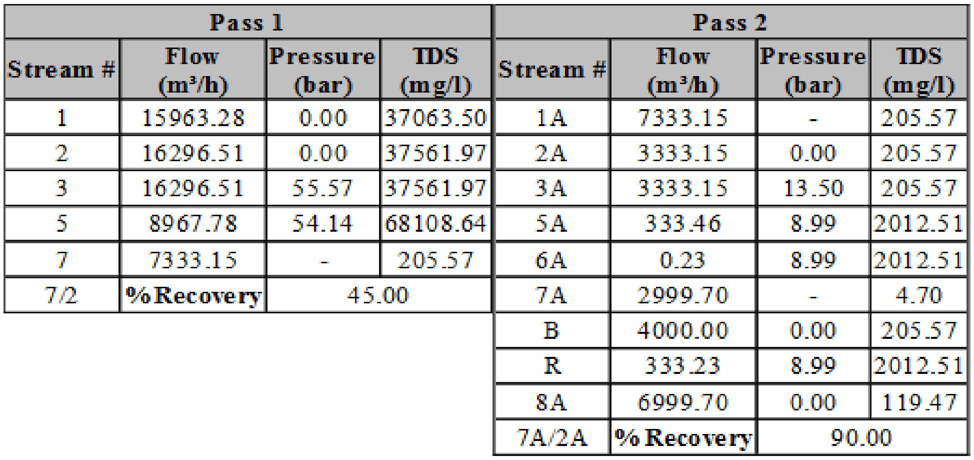
Pass 2

Feed Flow	Recovery	Permeate Flow	Flux	Final Permeate
3333.00 m³/h	90.00 %	2999.70 m³/h	34.95 lmh	6999.70 m³/h
	☑ Specify	☑ Specify		

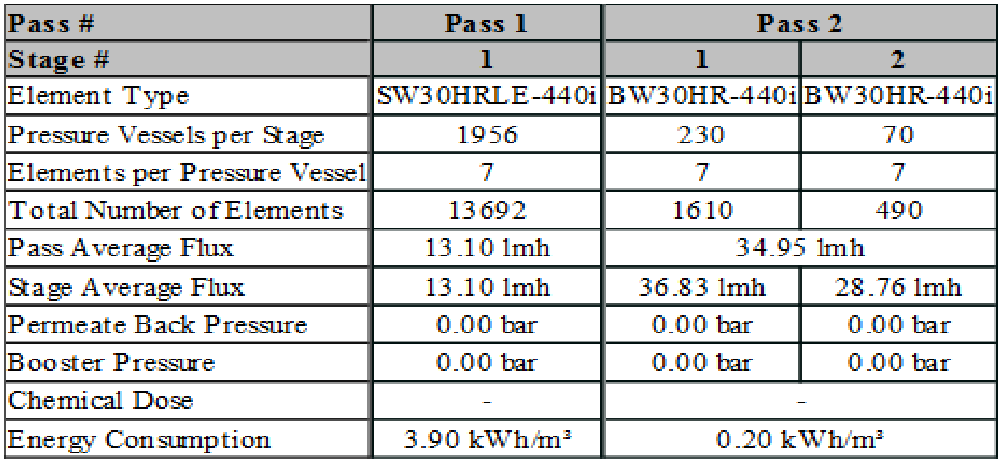
To calculate the system flows based on pass 2 product, specify two parameters in pass 2, plus one parameter in pass 1.

Fig 5.16: Flow Calculator in first and second pass (case 03)





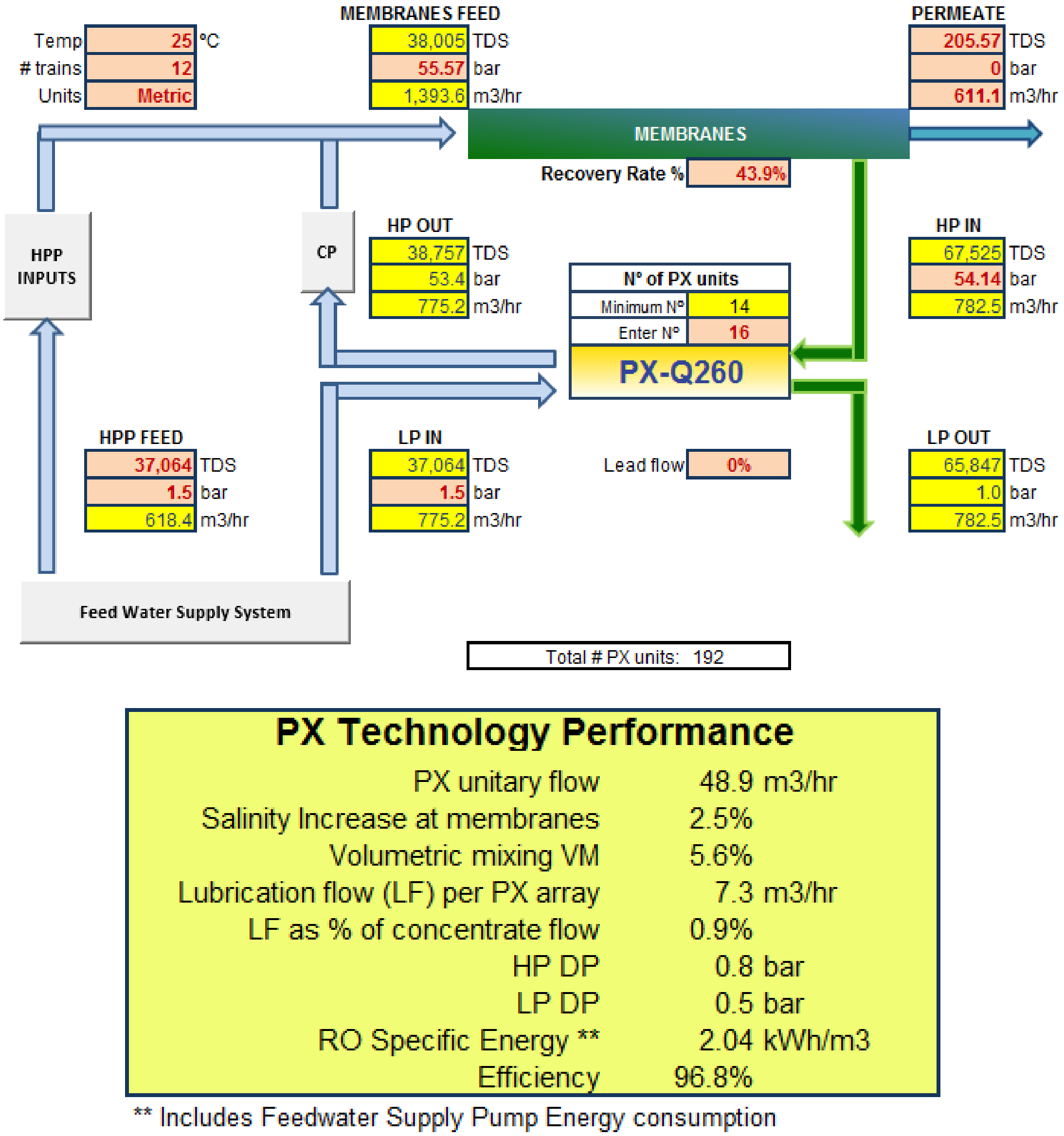
Pass 1				Pass 2			
Stream #	Flow (m^3/h)	Pressure (bar)	TDS (mg/l)	Stream #	Flow (m^3/h)	Pressure (bar)	TDS (mg/l)
1	15963.28	0.00	37063.50	1A	7333.15	-	205.57
2	16296.51	0.00	37561.97	2A	3333.15	0.00	205.57
3	16296.51	55.57	37561.97	3A	3333.15	13.50	205.57
5	8967.78	54.14	68108.64	5A	333.46	8.99	2012.51
7	7333.15	-	205.57	6A	0.23	8.99	2012.51
7/2	**%Recovery**	45.00		7A	2999.70	-	4.70
				B	4000.00	0.00	205.57
				R	333.23	8.99	2012.51
				8A	6999.70	0.00	119.47
				7A/2A	**%Recovery**	90.00	



Pass #	**Pass 1**	**Pass 2**	
Stage #	**1**	**1**	**2**
Element Type	SW30HRLE-440i	BW30HR-440i	BW30HR-440i
Pressure Vessels per Stage	1956	230	70
Elements per Pressure Vessel	7	7	7
Total Number of Elements	13692	1610	490
Pass Average Flux	13.10 lmh	34.95 lmh	
Stage Average Flux	13.10 lmh	36.83 lmh	28.76 lmh
Permeate Back Pressure	0.00 bar	0.00 bar	0.00 bar
Booster Pressure	0.00 bar	0.00 bar	0.00 bar
Chemical Dose	-	-	
Energy Consumption	3.90 kWh/m³	0.20 kWh/m³	

Fig 5.17: Flow diagram of the process in first and second diagram (case 03)

Energy consumption of the system by using energy recovery



PX Technology Performance

PX unitary flow	48.9 m3/hr
Salinity Increase at membranes	2.5%
Volumetric mixing VM	5.6%
Lubrication flow (LF) per PX array	7.3 m3/hr
LF as % of concentrate flow	0.9%
HP DP	0.8 bar
LP DP	0.5 bar
RO Specific Energy **	2.04 kWh/m3
Efficiency	96.8%

** Includes Feedwater Supply Pump Energy consumption

Fig 5.18: ERI^{TM} PX^{TM} power model results (case 03)

The figure 5.18 shows ERI^{TM} PX^{TM} power model modeling outputs with combination of ROSA software such as membrane feed and permeate characteristics and concentrate parameters.

The plant will contains 12 array of pressure exchanger each array has 16 PX-Q260 units with efficiency 96.8%, flow rate 48.9m^3/hour and volumetric mixing 7.3%, the energy consumption reduced to 2.04Kwh/m^3.

Pump Efficiency:

The pump efficiency assumed 88%, since larger pumps generally have higher specific speed and more efficient.

Membrane element type:

For membrane element (SW30XHR-440i), the Active area = 40.9 m^2 and the flow rate = 25 m^3/day. The required feed pressure is 60bar in case 01 and 57.77 bar in case 02.

For membrane element (SW30HRLE-440i), the Active area = 40.9 m^2 and the flow rate = 31m^3/day. The required feed pressure is 55.57 bar in case 03.

Therefore; the element has direct effect on the energy consumption.

Flow factor (Fouling Factor):

As the flow factor is set as1.0 for new membrane element, to optimize membrane performance as seasonal variations in the seawater occur or as the membrane elements age the flow factor 0.85. For instance, if heavy fouling conditions occur, the recovery rate can be lowered, increasing membrane cross flow and reducing contaminant deposition and biological growth on membrane surfaces.

Recovery:

As recovery rate is reduced, the reject water concentration reduces and the osmotic pressure in the membrane elements decreases accordingly. Reducing recovery essentially dilutes the concentrate stream which reduces the membrane feed pressure. This reduces the load on the high-pressure-pump motor. As recovery rate is increased, membrane feed pressure increases but the SWRO system requires less feed water.

Pressure exchanger:

The pressure exchanger is preferred due to its high efficiency, the selected model PX-Q260 reduced the power consumption with value 2.04 kW/m^3.

Specific Energy:

The specific energy is calculated from total power consumed by pumping system divided by total permeate flow. The optimal (minimum) value can be achieved by different scenarios as following:

- Increasing permeate flow quantity with keeping power consumption constant.
- Increasing permeate flow quantity larger than the increasing power consumption.
- Decreasing the power consumption with keeping permeate flow quantity.
- Decreasing the power consumption with quantity larger than decreasing the flow rate.

After performing several trials by Rosa software and ERI™ PX™ power model, the resulted values are illustrated below in table 5.01.

Table 5.01: Summary of Final Results

Specific Energy Consumption (SEC)	**Case 01**	**Case 02**	**Case 03**
SEC without PX (1st Pass)	4.07	4.05	3.90
SEC with PX (1st Pass)	2.22	2.13	2.04
SEC (2nd Pass)	0.15	0.43	0.20
Total	**2.37** Kwh/m^3	**2.56** Kwh/m^3	**2.24** Kwh/m^3

Table 5.01shows the specific energy consumption in case 01 reduced from 4.07 Kw/m^3 to 2.22 Kw/m^3 after addition the pressure exchanger PX-260 with efficiency 97.1%.

In case 02 the specific energy consumption reduced from 4.05 Kw/m^3 to 2.13 Kw/m^3 by using the pressure exchanger Px-260 with efficiency 96.8%

In case 03 the optimal specific energy consumption value 2.24 Kw/m^3 is achieved after using pressure exchanger with efficiency 96.8% and using membrane element SW30HRLE-440i with active area 40.9 m^2 and flow rate 30m^3/day.

In addition using large centrifugal pump with high efficiency reached up to 88% contributed in reduction of energy consumption in the system.

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The main controlling factors that have potential effect on power consumption are membrane elements, high pressure pumps, energy recovery devices. From this research the following concluding remarks can be outlined:

- For plant design and determination of the specific energy consumption of the SWRO, an SWRO plant calculation and design model was used, which covers different RO configurations and the design and energy consumption of the SWRO plant systems. A characteristic SWRO plant size capacity (140,000 m^3/d) and configuration (two pass RO system) was selected for modelling purposes. With the most efficient energy recovery system, specific energy consumption under the modelling conditions for the 1^{st} pass and 2^{nd} pass of the SWRO plant is about 2.04 and 0.20 kWh/m^3 respectively.
- In the first pass, without using ERD, the SEC for all trains varies between 3.90 and 4 kWh/m^3.While by using ERDs, the SEC for all trains varies between 2.04 and 2.13 kWh/m^3.
- By introducing the PX, a 46% power saving and size reduction of the high pressure pump is possible at 45% product recovery in SWRO plant.
- Staging is a function of hydraulics, so it is important to maintain the fluid velocity in the membranes above the minimum requirement.
- The partial two passes system can produce the required permeate quality, this configuration results in smaller second pass unit; therefore lower capital and operating costs, as well as higher combined permeate recovery rate (utilization of the feed water).
- Plant performance is consistent with the design goals which are pre-determined.
- The three center design is an attractive solution for large desalination plants due to its benefit of power saving and plant availability.

- Maximum pumping efficiency depends on good pump design & proper design of SWRO system completely.
- ERD performance is mainly dependent on the operating parameters such as flow and pressure.
- The active area and flow capacity are the most effecting parameters of membrane element performance.
- Membrane system flux does not have to change with the change in membrane types because the feed water quality determines the maximum membrane flux.
- Large plants preferable to split up into a number of identical trains. Then the number of trains in service can be adjusted to the needs to achieve the most flexible & reliable operating conditions.
- The high efficiency energy recovery devices will become the most popular process for RO seawater desalination process in the near future.
- Due to advances in the efficiency of energy recovery systems the performance of the SWRO plants has been increased in the last decade.
- Optimization problem formulation is presented to minimize an objective function while optimizing design and operating parameters of the process. It is found that considerable reduction in pumping cost is achievable. Furthermore, commercial module designs might be further refined in order to reach more economic improvements for RO processes subject to technical limitations.
- The main technological improvements have come from the optimized process design and improved equipment. Process development such as two pass, split partial permeate treatment, have proven to be cost effective.
- Most modern SWRO desalination plants save energy by utilizing isobaric energy recovery devices such as the (ERI PX) Pressure Exchanger device.
- The behavior of the membrane element affects the operation conditions (fouling factor; 0.85), a differential pressure and a system salt passage.
- The membrane type selection make a substantial contribution toward the energy consumption. (Affecting the operating pressure).

6.2 Recommendations

The power consumption is a very key factor in total operation cost of desalination plants. Accordingly, the following recommendations should be considered:

- It very important to establish the finished water quality goals when starting the design of SWRO system.
- The usage of energy recovery devices is useful in designing a new SWRO system or expanding of the existing one.
- An extensive researches should be focused on the membranes performance improvement, energy recovery enhancement and reliable plant design.
- Most operating data should be monitored, recorded and reviewed to normalize the plant performance.
- A pilot plant should be run for a specific period of time more than one year to optimize SWRO desalination plant performance effectively and efficiently, when it goes on stream.
- In order to determine the robustness of the methodology, the model requires some additions such as energy recovery calculations, especially for the design of an actual SWRO system.
- Although the desalination technologies are mature enough to be a reliable source of fresh water from the sea, A significant amount of research and development (R&D) should be carry out in order to constantly improve the technologies and reduce the cost of desalination. Long term multidisciplinary and integrated R&D programs are needed for the purpose of making the seawater desalination techniques affordable worldwide.
- High-pressure pumps have to be properly designed to operate with maximum efficiency and maintenance simplicity. Energy Recovery devices have to form a unitary block, capable of changing pumping flow independently of high-pressure pumps.
- For energy efficiency improvement in pumping system, the optimal pump sizing and pump operational conditions should be taken in considerations.
- Integration of advanced high-pressure pumps and energy recovery systems in seawater RO systems will yield to reduction in power consumption and operating cost.

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Appendix (A)

ROSA RESULTS