DESIGN, MODELING AND OPTIMIZATION OF A SEAWATER REVERSE OSMOSIS DESALINATION PLANT

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20th SEPTEMBER 2021

As the candidate's supervisor, I have approved this dissertation for submission.

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This section presents the articles that form part and/or include the research presented in this thesis. The following papers have been published or are have been accepted for publication:

DoHET Accredited Journals

1. **Randy Ncube** and Freddie L. Inambao, Sea Water Reverse Osmosis Desalination: Energy and Economic Analysis. *International Journal of Mechanical Engineering and Technology 10(12), 2019, pp. 716-731.* http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=10&IType=12
2. **Randy Ncube** and Freddie L. Inambao, A Review of Desalination Systems using the Reverse Osmosis Technique. *International Journal of Mechanical Engineering and Technology 10(11), 2019, pp. 353-370.* http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=10&IType=11
3. **Randy Ncube** and Freddie L. Inambao, Modelling and Optimization of Reverse Osmosis Desalination Plants. *International Journal of Mechanical Engineering and Technology. 10(12), 2019, pp. 732-742.* http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=10&IType=12
4. **Randy Ncube** and Freddie L. Inambao, Membrane Modeling and Simulation for a Small Scale Reverse Osmosis Desalination Plant, *International Journal of Engineering Research and Technology. 13(12), 2020, pp. 4065-4083.* http://www.irphouse.com/ijert20/ijertv13n12_05.pdf
5. **Randy Ncube** and Freddie L. Inambao, Theoretical Data Analysis for a Small-Scale Reverse Osmosis Desalination Plant, *International Journal of Mechanical and Production Engineering Research and Development. 11(2), 2021, pp. 31-40.*

   http://www.tjprc.org/view_paper.php?id=15003

6. **Randy Ncube** and Freddie L. Inambao, Experimental Data Analysis for a Reverse Osmosis Desalination Plant, *International Journal of Mechanical and Production Engineering Research and Development. 11(3), 2021, pp. 421-440.* http://www.tjprc.org/view_paper.php?id=15210

7. **Randy Ncube** and Freddie L. Inambao, Modeling, Simulation and Optimization of a Reverse Osmosis Desalination Plant, *International Journal of Mechanical and Production Engineering Research and Development. 11(4), 2021, pp. 27-46.* http://www.tjprc.org/publishpapers/2-67-1623380010-3IJMPERDAUG20213.pdf
8. **Randy Ncube** and Freddie L. Inambao, Normalization of a Reverse Osmosis Desalination Plant, *International Journal of Mechanical and Production Engineering Research and Development*. *11(XX), 2021, pp. XX*.
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For all the publications the candidate is the main author while Prof. Freddie L. Inambao is the supervisor.

Dedication

This work is dedicated to the Almighty God who helped me overcome all challenges and obstacles during my research period and to my family, particularly to my dearest wife Nothando F. Poyah-Ncube and daughter Noluthando C. Ncube, for the support they gave me through the journey.

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Abstract

Potable water is one of the major needs for human, animals and plant survival. But recently, due to the growth in population and industrialization, fresh water shortage has escalated to alarming levels particularly in the Middle East and Africa. South Africa has not been spared in this predicament. Recently, Cape-town and its surrounding areas have been hard hit by water shortages and in one of the years, the region almost got to day zero, where all water sources were about to run dry, yet the region is surrounded by vast amounts of sea water. Research and development of several methods to mitigate this problem is still ongoing. Desalination of seawater is one of the several ways which have been used to ease this problem, and Reverse Osmosis (RO) is generally taking over as the preferred technique of desalination because of its generally higher efficiency and better quality of water produced using generally lower energy. Research has also shown that the limitations and concerns of using RO technique on water productivity are membrane fouling and high energy consumption in these plants. Design, modeling and optimization using modeling and simulation softwares and experiments on seawater reverse osmosis (SWRO) desalination plant is one of the ways in which this water shortage crisis may be alleviated.

This dissertation seeks to attend to the limitations of the available plants in use through experimentation, coming up with mathematical models and simulations to increase throughput and efficiency of the system. Theoretical data analysis and membrane modeling of a SWRO desalination unit was done on the design and undertaken using Hydranautics Nitto Group Company powered Integrated Membrane Solutions Design (IMSDesign) software, a membrane modeling software that allows users to design a reverse osmosis (RO) system based on Hydranautics membranes. The experiments were done on the Victoria and Alfred (V&A) Waterfront desalination unit, a seawater desalination plant located along the Atlantic Ocean coastal city of Capetown, South Africa. Extracted data from experiments was collected and statistically analyzed using Microsoft excel and different relationships of parameters were plotted. Some of the design input and output parameters that were studied using include feed and permeate TDS, pressure, temperature, pH, energy consumption and conductivity. The effects of different feed parameters were compared against their permeate variables in the month of November 2018, and several relationships and correlations were plotted. Experimental data showed that an increase in feed temperature resulted in a decrease in permeate TDS, whereas and increase in feed pressure

resulted in a general increase in permeate TDS. Finding the optimum compromise between the two input variables was done and optimum values were found. Energy efficiency and reducing energy consumption of the plant while not compromising on product quality is also one of the parameters that were studied and the relationships between feed TDS, feed temperature, feed pressure and feed pH against energy consumption were modelled.

Modeling and simulation using ROSA and IMSDesign softwares was undertaken and several equations and correlations of specific energy and input temperature, feed temperature and permeate TDS, feed TDs and permeate TDS were produced.

Optimization of the V & A desalination plant was performed using experimental data extracted from the plant and some assumed data. Simulation and optimization was accomplished using Water Application Value Engine simulation software and improvements in specific energy consumption, permeate TDS and permeate productivity were observed.

CHAPTER 1. Introductory Chapter

Introduction

“Water crisis” and “scarcity” is on everyone’s lips of late. The WHO states that the most obvious indicator in this regard is that about 1.2 billion people do not have access to safe and affordable water for their everyday use [1]. A huge percentage of the world’s population is subjected to water stress. In arid regions there is even more suffering because of the constraining effects of inadequate water resources [2]. The most important reasons for water shortages are growing water demand as a result of population increase, economic development, and increased per capita consumption of goods and services [3]. Supplies of clean water have become more critical in recent years owing to excessive use of, and ever increasing pollution of, natural water sources. Furthermore, drinking water demand has risen the world over and regulations on the quality of drinking water have become a lot tighter and tougher [4]. This global shortage of water stimulates the demand – and research – for more energy-efficient desalination technologies.

In South Africa the supply of water is limited, unfairly distributed, and climate change and the predominance of invasive alien plant species has a negative effect on it [5]. Surface water accounts for 77 % of total potable water use along with ground water (9 %) and recycled water (14%). The Limpopo and Komati rivers are the largest sources of water in South Africa [6]. However, these sources are not adequate and importation of water from the Lesotho highlands and from the Congo River offers a solution to the crisis but is costly to consumers [5]. Fig. 1-1 shows the geographic map of the major rivers supplying South Africa with fresh water. These rivers include the Limpopo River in the province of Limpopo, the Vaal River which cuts across 5 provinces including Gauteng and Mpumalanga, the Orange River which starts from Lesotho and flows through the Free State province to the North West and Northern Cape spilling out to the Atlantic Ocean. Lastly, the Tugela River serves KwaZulu-Natal province.

Figure 1-1 Geographical map showing major rivers in South Africa [6]

Water scarcity also poses a threat to food production, industry (mining and manufacturing) and the agricultural sector [7]. Agriculture and industry account for approximately 15 % and 29 % of the country's total GDP respectively, and these sectors use almost 84 % of the country's total water supply [6].

Scientists and engineers have studied this fresh water shortage crisis and have come up with different methods of obtaining fresh water from various water sources. One of the methods is desalination of sea (salty) and brackish water. Seawater desalination plays an important role in dealing with the challenges of global water scarcity. One of the most used desalination techniques is reverse osmosis (RO). The processes of RO have emerged as leaders in water desalination, purification and reuse applications. RO has proven that it can be used to produce drinking water at lower costs than other conventional thermal-based desalination technologies [8]. Even though reports of negative impacts have been made regarding existing plants, many positive aspects are present. Desalination has helped in industrial and agricultural production, and the preservation of existing natural water resources [9].

Membranes with high permeability, energy recovery devices, optimization of process configuration and control have been developed. These have significantly reduced the cost of RO processes and hugely improved process efficiency [10]. However, RO has its limitations as well, including membrane fouling and generally high energy consumption. This thesis seeks to attend to the limitations of existing plants in use through experimentation, coming up with mathematical models and simulations to increase throughput and efficiency of the RO system.

Problem Statement

A significant population of the world is under stress due to water scarcity [2]. Recent research has shown that almost 4 billion people are facing water shortages for at least one month in a calendar year and almost 500 million face fresh water stresses all year round. This is due to the ever increasing population, ever developing communities, increase in consumption patterns and growth in agricultural irrigation [11]. Africa, and particularly South Africa, has not been spared. South Africa is generally a water stressed country, with a population of around 51 million people, 40 % of whom live in the rural areas. About 74 % of this rural population depend on ground water, 19 % do not have access to potable water supply, and 33 % do not have proper basic sanitation. As if this is not enough, 45 % of clinics and over 26 % of schools (both rural and urban) have no access to clean water [6]. With the advent of Covid-19 and the need for safe and clean water at all times for sanitization and washing of hands, this is a cause for concern to all.

The 2014 to 2016 drought in South Africa initiated a policy debate on water security. Water security for future generations using affordable technologies was debated and recommendations were made to employ technologies to realign supply and demand were made [12]. The city of Cape Town, a massive tourist hub in the country, almost reached “day zero”, the projected date when the city’s potable water supply would have run dry [13]. The Cape region is surrounded by vast amounts of sea water, which, when proper technologies are applied, can remedy such a situation. Such technologies include thermal and membrane purification of water, the two most successful techniques, but RO desalination takes the lead [2]. Although RO has proven to be one of the most efficient techniques of desalination, it still has its limitations. These include membrane fouling through concentration polarization, energy consumption, maintenance and low recovery. This thesis seeks to improve the performance of the system through experimentation and optimization of the plants that are already in use.

Research Motivation

According to the United Nations (UN) Sustainable Development Goal number 6 (SDG 6), everyone must have access to safe and affordable drinking water and sanitation by 2030, and this requires extensive investment in adequate infrastructure and provision of sanitation facilities [14]. The UN also states that our planet has sufficient fresh water to achieve the SDG 6, but due to poor and inadequate investment in infrastructure, millions of people in the world die from diseases associated with inadequate water supply [15]. Water scarcity is projected to become more extensive in years to come. This requires renewed consideration of freshwater security and management [16]. The South African government is dedicated to achieving this goal by 2030 [17]. However, both rural and urban municipalities lack facilities that effectively and efficiently clean water and existing plants need improvement [6]. Thermal and membrane desalination processes are some of the technologies that can be employed to solve this water crisis. Sea water reverse osmosis (SWRO) is a desalination process that is generally energy efficient and produces the required permeate total dissolved salts (TDS) recommended for human consumption. It has its limitations though; membrane based desalination processes may achieve efficiencies of more than 40 % [16] but this is still generally low efficiency. Energy consumption of a SWRO desalination plant is generally high and optimization of the design without compromising on the quality of the output is of paramount importance. The Gulf region, particularly Saudi Arabia, Oman, United Arab Emirates (UAE), Qatar, Kuwait, and Bahrain lead the way in the mitigation of water scarcity through desalination [18]. Africa needs to invest in research of this process so as to lessen the effects of water scarcity in the long run. Research and development is needed to come up with more energy efficient systems that will achieve the same output quality with minimum energy consumed.

Aim and Objectives

The aim of this project was to design, model and optimize a SWRO desalination plant through experimentation on an already operational plant, extract data, and come up with models and simulations of the system. The objectives of this research were:

1. To conduct experiments on an already operational SWRO plant;

2. To extract data and develop mathematical modeling;
3. To perform analysis and optimization of the system; and
4. To develop an efficient design of the plant with optimum conditions for potable water production.

Research Significance

Africa and the Middle East regions are the hardest hit areas when it comes to water scarcity due to low surface water and groundwater resources. This has necessitated research in alternative supplies of potable water derived from brackish water and seawater, which will be energy efficient while at the same time not compromising the quality of the output permeate water. Africa in particular is the least technologically advanced continent, with most of the population living under rural conditions with no clean water supply. This study will help to alleviate this problem.

Thesis Outline

This thesis contains chapters that are in line with the aims and objectives of the research conducted. Most of the chapters take the form of journal articles and publications through various publishing houses. The thesis comprises nine chapters.

Chapter 1: The Introductory Chapter introduces the topic, the research significance, aim and objectives, problem statement and scope of the thesis.

Chapter 2: The literature review, which is a critical review of the desalination process using RO.

Chapter 3: Seawater Reverse osmosis desalination: energy and economic analysis, where the experimental research was conducted.

Chapter 4: Modeling and optimization of SWRO desalination plants.

Chapter 5: Membrane modeling and simulation for a RO desalination plant – membranes are one of the most important components in desalination.

Chapter 6: Theoretical data analysis of a RO desalination unit. This involves the use of data extracted from the Hydranautics Nitto Group Company powered Integrated Membrane Solutions Design (IMSDesign) software membrane modeling software.

Chapter 7: The experimental work conducted on the Victoria and Alfred (V&A) Waterfront desalination unit, a seawater desalination plant located in Cape Town, South Africa, a city on the Atlantic ocean. Extracted data from experiments was collected and statistically analyzed using Microsoft Excel and different relationships of parameters were plotted.

Chapter 8: Mathematical modeling, simulation and optimization of the plant using WAVE modeling and simulation software with several correlations of specific energy and input temperature, feed temperature and permeate temperature, feed and permeate TDS.

Chapter 9: Presentation of the results and conclusions of the research. The chapter also outlines recommendations for future work.

Scope

This thesis covers work related to modeling, simulation and optimization of a SWRO desalination plant.

References

1. Rijsberman, F.R., Water scarcity: fact or fiction? *Agricultural Water Management*, **80**(1-3): 2006, pp. 5-22. DOI: https://doi.org/10.1016/j.agwat.2005.07.001.
2. Goosen, M., S. Sablani, H. Al-Hinai, S. Al-Obeidani, R. Al-Belushi, and A. Jackson, Fouling of reverse osmosis and ultrafiltration membranes: A critical review. *Separation Science and Technology*, **39**(10): 2005, pp. 2261-2297. DOI: https://doi.org/10.1081/SS-120039343.
3. Shaffer, D.L., N.Y. Yip, J. Gilron, and M. Elimelech, Seawater desalination for agriculture by integrated forward and reverse osmosis: Improved product water quality for potentially

less energy. *Journal of Membrane Science*, **415**: 2012, pp. 1-8. DOI: https://doi.org/10.1016/j.memsci.2012.05.016.
4. Matin, A., Z. Khan, S. Zaidi, and M. Boyce, Biofouling in reverse osmosis membranes for seawater desalination: Phenomena and prevention. *Desalination*, **281**: 2011, pp. 1-16 DOI: 10.1016/j.desal.2011.06.063.
5. Blignaut, J. and J. Van Heerden, The impact of water scarcity on economic development initiatives. *Water SA*, **35**(4): 2009, DOI: http://dx.doi.org/10.4314/wsa.v35i4.76800.
6. Mission2017. *Water access in South Africa*. 2017. Available from: http://12.000.scripts.mit.edu/mission2017/case-studies/water-access-in-south-africa/#:~:text=Currently%2C%20South%20Africa%20has%20access,total%20use)%20%5B1%5D.&text=On%20the%20other%20hand%2C%20cities,and%20Komati%20rivers%20%5B1%5D.
7. Dinar, A., A. Tieu, and H. Huynh, Water scarcity impacts on global food production. *Global Food Security*, **23**: 2019, pp. 212-226. DOI: https://doi.org/10.1016/j.gfs.2019.07.007.
8. Duan, J., Y. Pan, F. Pacheco, E. Litwiller, Z. Lai, and I. Pinnau, High-performance polyamide thin-film-nanocomposite reverse osmosis membranes containing hydrophobic zeolitic imidazolate framework-8. *Journal of Membrane Science*, **476**: 2015, pp. 303-310. DOI: https://doi.org/10.1016/j.memsci.2014.11.038.
9. Tularam, G.A. and M. Ilahee, Environmental concerns of desalinating seawater using reverse osmosis. *Journal of Environmental Monitoring*, **9**(8): 2007, pp. 805-813. DOI: 10.1039/b708455m.
10. Lee, T., A. Rahardianto, and Y. Cohen, Flexible reverse osmosis (FLERO) desalination. *Desalination*, **452**: 2019, pp. 123-131 DOI: https://doi.org/10.1016/j.desal.2018.10.022.
11. Mekonnen, M.M. and A.Y. Hoekstra, Four billion people facing severe water scarcity. *Science Advances*, **2**(2): 2016. DOI: https://doi.org/10.1126/sciadv.1500323.
12. Donnenfeld, Z., S. Hedden, and C. Crookes, A delicate balance: Water scarcity in South Africa. 2018. DOI: https://hdl.handle.net/10520/EJC-1486c3180a.
13. Maxmen, A., As Cape Town water crisis deepens, scientists prepare for 'Day Zero'. *Nature*, **554**(7690): 2018. Available from: https://go.gale.com/ps/anonymous?id=GALE%7CA525862811&sid=googleScholar&v=2.1&it=r&linkaccess=abs&issn=00280836&p=HRCA&sw=w.
14. Programme, U.N.D. Goal 6: Clean water and sanitation. 2021. Available from: https://www.undp.org/content/undp/en/home/sustainable-development-goals/goal-6-clean-water-and-sanitation.html.
15. Tacker, S., Ensure access to water and sanitation for all. 2018. Available from: https://sdg-tracker.org/water-and-sanitation.
16. Davenport, D.M., A. Deshmukh, J.R. Werber, and M. Elimelech, High-pressure reverse osmosis for energy-efficient hypersaline brine desalination: current status, design considerations, and research needs. *Environmental Science & Technology Letters*, **5**(8): 2018, pp. 467-475 DOI: https://doi.org/10.1021/acs.estlett.8b00274.
17. Matona, T. *South Africa's Implementation of the 2030 Agenda for Sustainable Development: Voluntary National Report*. 2019. Available from: https://sustainabledevelopment.un.org/content/documents/23402SOUTH_AFRICA_RSA_Voluntary_National_Review_Report_Final__14_June_2019.pdf.

18. Alsarayreh, A.A., M.A. Al-Obaidi, R. Patel, and I.M. Mujtaba, Scope and limitations of modelling, simulation, and optimisation of a spiral wound reverse osmosis process-based water desalination. *Processes*, **8**(5): 2020, pp. 573 DOI: https://doi.org/10.3390/pr8050573.

CHAPTER 2. A Review of Desalination Systems using the Reverse Osmosis Technique

The author is reviewing the projects done by other researchers and scholars in the field of desalination using reverse osmosis and other methods used. The article was published in the International Journal of Mechanical Engineering and Technology (IJMET).

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A REVIEW OF DESALINATION SYSTEMS USING THE REVERSE OSMOSIS TECHNIQUE

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ABSTRACT

Water is and has always been the source of life for humans, animals and every other living organism, but its availability is slowly diminishing by the day. Scarcity of potable and fresh water is a major concern the world over, especially in the Middle East and Africa. There is a need for new, energy efficient and eco-friendly ways of producing fresh water from the vast and abundant sources of saline and brackish water available. Desalination is one of the several ways which have been used to mitigate this problem, and Reverse Osmosis (RO) is generally taking over as the preferred technique of desalination because of its generally higher efficiency and better quality of water produced using generally lower energy. Review of many scholarly articles have shown that the limitations and concerns of using RO technique on water productivity are membrane fouling and high energy consumption in small scale plants. Therefore, efficient energy and membrane solutions are required. The main objective of this paper is to review current and already developed RO desalination methods, membranes and the mathematical modelling and optimization of RO systems using Genetic Algorithm.

Keywords: Desalination, Reverse Osmosis.

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http://www.iaeme.com/IJMET/issues.asp?JType=IJMET&VType=10&IType=11

1. INTRODUCTION

'Water crisis' and 'water scarcity' are the words on everyone's lips of late. The WHO states that about 1.2 billion people do not have access to safe and affordable water for their everyday use [1]. The most important reasons for water shortages are growing water demands from population increase, economic development, and increased per capita consumption of goods and services [2]. In South Africa the supply of water is limited, unfairly distributed, and climate change and the predominance of invasive alien plant species has a negative effect on it. Importation of water from Lesotho and from the Congo River offers a solution to the crisis but will prove to be very costly to consumers [3]. A huge percentage of the world's population is subjected to water stress. In the arid regions, there is more suffering because of the constraining effects of inadequate water resources [4]. Supplies of clean water have become more critical in recent years due to the excessive use of and the ever increasing pollution of natural water sources. Furthermore, drinking water demands have risen of late world over and the regulations on the quality of drinking water have become a lot tighter and tougher [5]. This global shortage of water pushes the demand and research for more energy-efficient desalination technologies. Reverse osmosis (RO) has proven that it can be used to produce drinking water at lower costs than the other conventional thermal-based desalination technologies [6]. Desalination has helped in industry maintenance, agricultural production, and the preservation of existing natural water resources [7]. The processes of Reverse osmosis (RO) have emerged as leaders in water desalination, purification and reuse applications. Membranes with high permeability, energy recovery devices, optimization of process configuration and control have been developed. These have significantly reduced the cost of RO processes and hugely improved process efficiency [8].

2. DESALINATION

Desalination is a process in which saline water is separated into two parts, one that has a low concentration of dissolved salts, which is called fresh water, and the other which has a much higher concentration of dissolved salts than the original feed water, which is usually referred to as brine concentrate [9]. Other than the fact that desalination might be the only choice for some countries and regions, there are drivers behind its development potential making it more favourable than conventional resource development. A primary advantage is its identification as a reliable source of supply because it is independent of climatic conditions and changes, rainfall and other weather patterns [10]. Over the last 30 years, desalination has made great progress in many arid regions of the world such as the Middle East and the Mediterranean. Technological advancements and the accompanying reduction in water production costs over the past years have expanded its use in areas which were traditionally supplied with fresh-water resources. While presently desalination provides only about 1.5% of the water supply world-wide, it is projected that in the next decade the production of new desalination systems will grow exponentially because of the unpredictable climate patterns prompted by global warming combined with growth in population pressures, limited availability of new and reasonably priced terrestrial water sources, and dramatic advancements in membrane technology which are expected to further decrease the cost and energy use of the desalination process [11]. Many countries in the world have started using desalination technologies but the Middle East has implemented this process on a large scale. Spain and Italy are the major users of desalination technology in Europe. Table 1 shows the top 10 countries using desalination technologies [12].

Table 1. Top 10 countries using desalination technologies [12].

Rank	Country	Capacity (million m3/d)	Market Share (%)
1	Saudi Arabia	9.9	16.5
2	USA	8.4	14.0
3	UAE	7.5	12.5
4	Spain	5.3	8.9
5	Kuwait	2.5	4.2
6	China	2.4	4.0
7	Japan	1.6	2.6
8	Qatar	1.4	2.4
9	Algeria	1.4	2.3
10	Australia	1.2	2.0

Several desalination processes have been developed, with many more currently under research and development. The most widely used and commercially proven technologies can be divided into 2 types: phase change thermal processes and membrane processes [9].

2.1. Types of Desalination

With the increasing volume and demand, different types of desalting technologies have been developed. Table 2 shows the available desalination technologies in use [12].

Table 2. Desalination technologies commercially in use [12].

Thermal	Membrane	Others
Multi-stage flash distillation	Reverse osmosis	Solar humidification
Multi-effect distillation	Electro-dialysis	Freezing distillation
Vapour compression	Forward osmosis	Ion exchange

Current desalination processes require huge amounts of energy, that is electrical energy, to run different types of pumps (high pressure pumps, pumps to transport liquid stream) for the RO process, or thermal energy to heat steam for the evaporation process in thermal desalination plants such as Multiple Effect Distillation (MED) and Multi Stage Flash (MSF). Therefore, the reduction of energy consumption to produce fresh water is one of the most active research areas in the desalination industry [13].

2.2. Reverse Osmosis and Reverse Osmosis Desalination

RO is a process in which saline water is pumped, under pressure, through a semipermeable membrane to reach osmotic pressure and allow water through the membrane. This method requires very high pressure and the cost of operation of a reverse osmosis plant is therefore high [14]. In general, a RO desalination system consists of 4 stages namely the intake, pre-treatment, RO membrane units and post treatment stage. Recently, there has been a considerable growth in the application of RO processes in major desalination processes. A RO purification system incorporates a semi-permeable membrane to remove unwanted matter which generally cannot be easily removed using other conventional treatments methods [15]. There are several parameters such as feed pressure as well operational temperature and membrane properties which affect the performance of RO process. It is of paramount importance to understand and apprehend the mechanism of the RO process so as to improve performance and reduce energy consumption [16]. RO desalination plants have been widely used for water and wastewater treatment, particularly in the areas where water is scarce. The performance of the RO process is strongly influenced by the temperature of feed water as a result of the effect of a reduction in solution viscosity and enlargement of membrane pores which, consequently, increases permeate production [17]. The efficiency of the process is affected by the operational parameters, the membrane and also the feed water properties [18]. Figure 1 shows a schematic diagram of a desalination system.

The design of a RO process includes the following three key components:

- The technical modeling of RO equipment and a systematic method for RO process synthesis.
- Accurate key performances indicators for the RO process characterization.
- The optimization procedure for the RO process optimization problem [20].

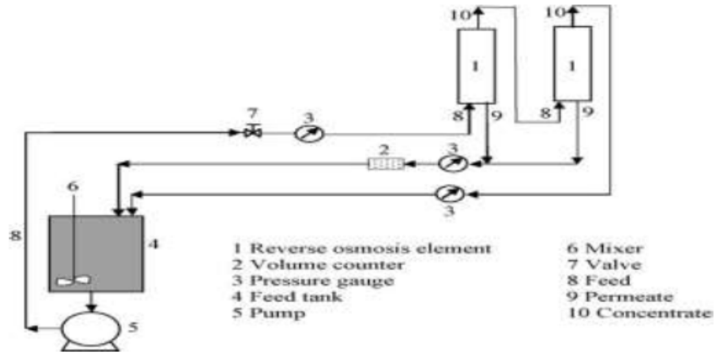

Figure 1. An example of the schematic diagram of a RO desalination system [19].

2.3. Membranes

The RO membranes most generally used for desalination at present are a composition of a semipermeable thin film (0.2 μm), made of either aromatic polyamide (PA) or cellulose acetate (CA), which is supported by a 0.025 mm to 0.050 mm microporous layer that in turn is cast on a layer of reinforcing fabric. The 0.2 μm ultrathin polymeric film is the characteristic that gives the RO membrane its salt rejection abilities and features [11]. Most membrane technologies are less robust and incapable of self-cleaning, necessitating chemical treatments for cleaning and recycling [21]. The cost of desalted water can be significantly reduced if high permeability membranes are used, although they display an increase in the salt passage. The reduction cost of water production can be obtained from either:

- Energy savings, due to the lower operating pressures required, or
- Increase in permeate production, as the plant will be operating at increased flux and recovery.

High permeability can be achieved through the proper incorporation of nanoparticles within inter-facially formed thin film nanocomposite membranes, for example, NanoH_2O [22].

2.3.1. Spiral Wound Membranes

A spiral-wound reverse osmosis module has a cylindrical configuration; it is in effect a flat-sheet, cross flow device (Figure 2). The feed water enters and passes through the module axially, while permeate moves spirally in a radial direction toward the permeate collection tube. The membrane which is interposed between these streams basically remains as the technological centrepiece of the module, while other features of module engineering are increasingly critical to performance [23]. A spiral wound membrane module is broadly used in RO industrial applications owing to its high packing density and its lower capital and costs of operating [24]. It also has a high membrane surface area to volume ratio, is easy to replace when worn out and it can be produced from a wide variety of materials [25].

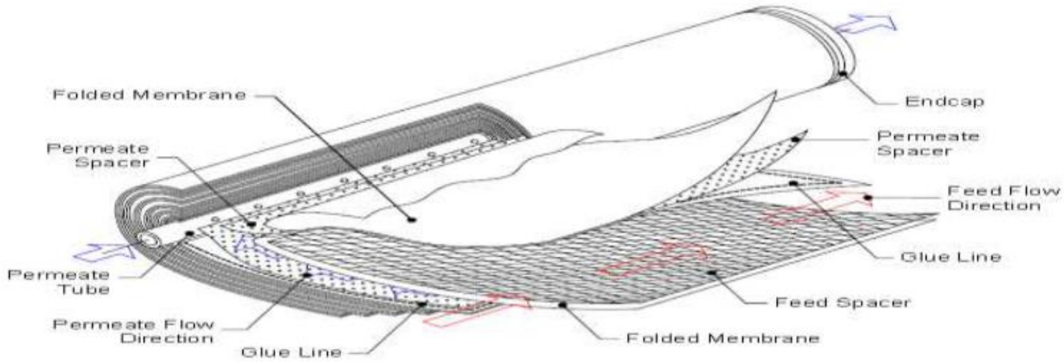

Figure 2. Spiral wound membrane configuration for RO [23].

2.3.2. Carbon Nanotubes

Carbon nanotubes (CNTs) are favourable materials for the next generation thin film because of the high flow rate of water through it and its excellent selectivity in permeability. CNTs consist of special molecules made up of carbon atoms in a unique arrangement. A CNT is hollow shaped and is in the region of above 50 000 times thinner than a human hair [14]. CNTs can overcome the disadvantages and limitations of conventional membranes. Furthermore, the surface is graphite which is hydrophobic in nature [26]. Most polymeric membranes are known to have shortcomings from a trade-off between selectivity and permeability, and in other instances, are also prone to fouling or show low chemical resistance. However, membranes based on CNTs offer a possible way to overcome these susceptibilities with a number of interesting structures emerging [27] (see for instance Figure 3).

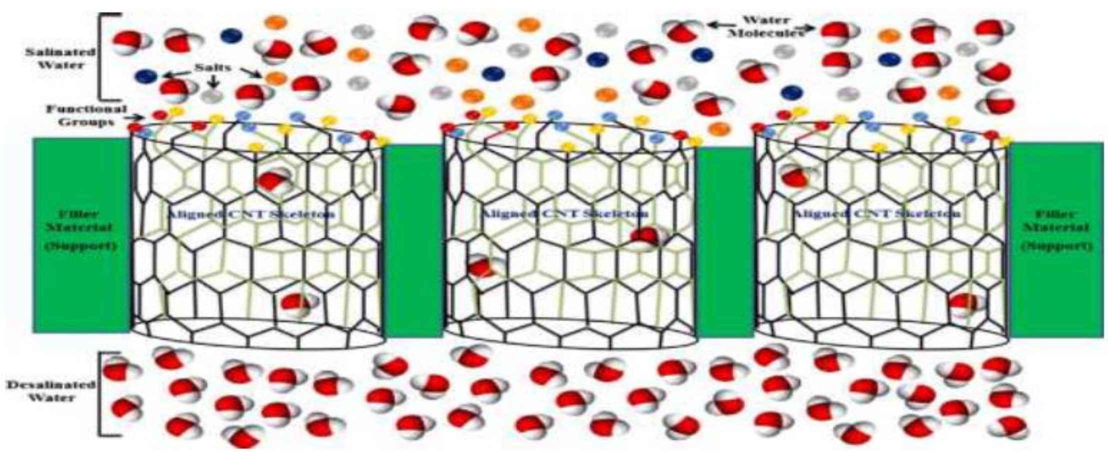

Figure 3. Illustration of desalination using CNTs [21].

2.3.3. Membrane fouling

Fouling of the membrane is a result of the build-up of unwanted materials on, in, or near the membrane [28]. Membrane fouling is the major hindrance for most applications in the water treatment and desalination industry, particularly when high concentrations of natural organic and inorganic matter occur. It increases resistance and this, in turn reduces the permeate flux of the membrane. This fouling can be categorized into three parts namely inorganic, organic, and biofouling [29]. Membrane fouling reduces water production rate, increases the consumption of power, and periodical Cleaning-in-Place (CIP) procedures for membranes are required [30]. It is an issue which has been studied globally (Figure 4).

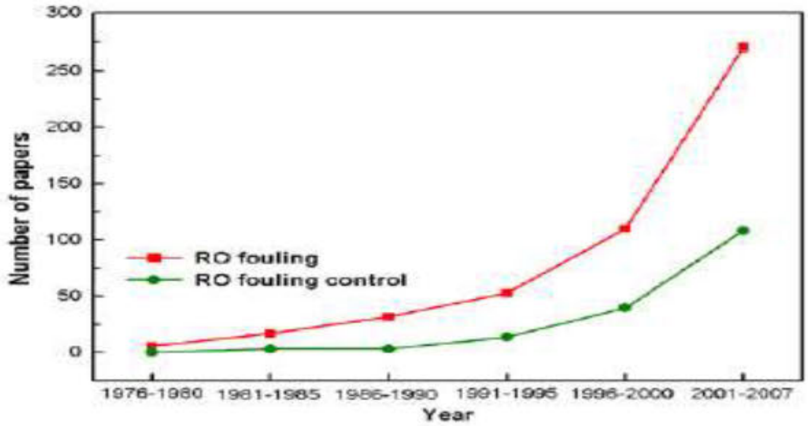

Figure 4. The number of publications on RO fouling and RO control against time [30]

This may result in low effectiveness, high costs and adds environmental issues related to the CIP solutions disposal.

The resistances which are responsible for reducing flux are calculated by the following equation:

$$R_T = R_m + R_{cp} + R_c + R_p \quad (1)$$

Where: R_T – Total Resistance during filtration,

R_m – Membrane Resistance,

R_{cp} – Concentration Polarization Resistance,

R_c – Cake Resistance,

R_p – Pore Blocking Resistance.

Generally, there are two fouling mechanisms in membrane processes: surface fouling and fouling in pores. But RO membranes have no distinguishable pores and are deemed to be essentially non-porous. Therefore, for RO membranes, the main fouling mechanism is surface fouling. Surface fouling may result from a variety of contaminants, including suspended particulate matter (inorganic or organic), dissolved organic matter, dissolved solids, and biogenic material. The capacity of water to foul RO membranes is frequently described using the silt density index, or SDI. The SDI of water is the fouling rate of a 0.45 mm filter at a pressure of 207 kPa (30 psi) and is described in the ASTM standard method D4189. The equation used to calculate SDI is given below:

$$SDI = \frac{100\% * (1 - \frac{t_1}{t_2})}{t} \quad (2)$$

Where: t – the total elapsed flow time, and t_1 and t_2 are the times (in seconds) required to filter 500 mL of water initially and after t minutes respectively [31]. There are other membrane fouling types such as irreversible adsorption and reversible sorption of hydrophobic substances and compounds within the membrane surface and membrane phase respectively. The reversible sorption tool yields smaller K_w values when compared with water; this is due to the increased frictional resistance in conjunction with a reduction in the content of water of the membrane [32].

3. MODELING AND OPTIMISATION OF RO SYSTEM

The mathematical modelling of any process incorporates two basic approaches: (i) theoretical (or parametric) models established on fundamental knowledge (mechanisms) of the process, also known as the knowledge-based approach and (ii) empirical (or non-parametric) models, which do not include the knowing of fundamentals principles governing the process [33]. There is no easier way to appropriately select desalination technologies for a given case. Iterations are the most probable approaches to be undertaken. Assessments of regional water demands and cost and economic viabilities should be taken into consideration. The researcher should handle critical information that include feed water quantity and quality and specifications of desalinated water [34] (see Figure 5).

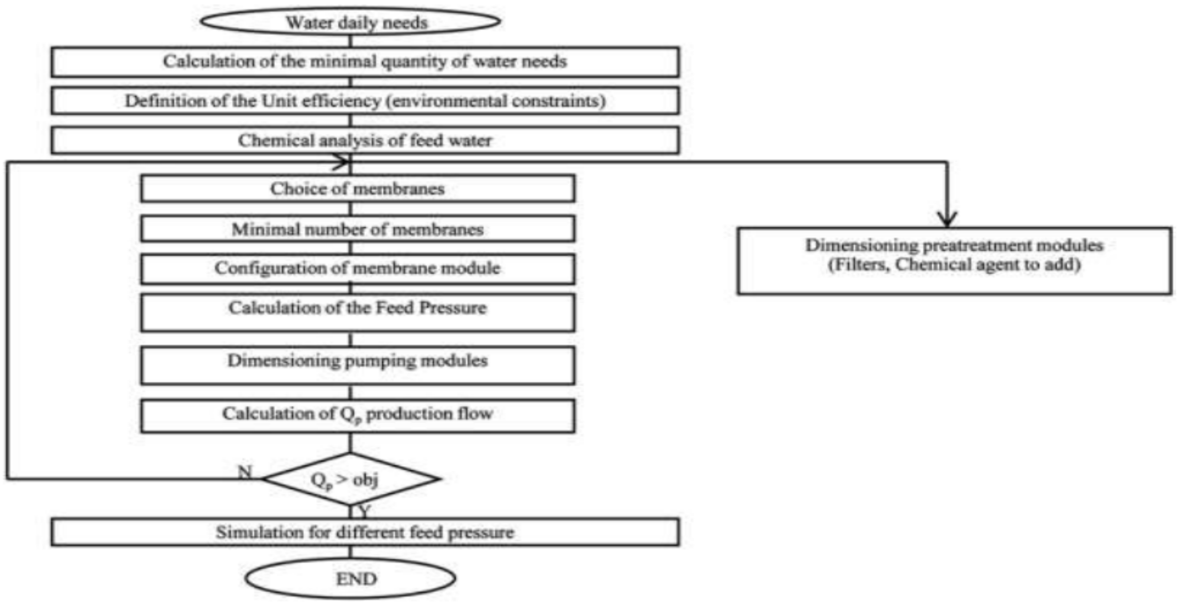

Figure 5. A RO unit design model flow chart [34].

A model of mass transfer solution–diffusion has been widely proposed by many scholars. The model is primarily established on two parameters: the water permeability, *A*, and the solute transport parameter, *B*. According to the model, the permeate flow rate, Q_p ($m^3 h^{-1}$), and the concentration, C_p (μLL^{-1}), are found through the following procedure:

$$Q_p = 3.6 * 10^6\ AS(\Delta P - \Delta \Pi) \quad (3)$$

$$C_p = \frac{B(C_O - C_p)}{A(\Delta P - \Delta \Pi)} \quad 4)$$

$$\Pi = \frac{0.2641C * (T^o + 273)}{1.0 * 10^6 - C} \quad (5)$$

$$\Delta P = \frac{P_f + P_b}{2} - P_p \quad (6)$$

$$C_O = \frac{C_f + C_b}{2} \quad (7)$$

Where: S (m^2) is the module surface area

P (MPa) is the difference of trans-membrane pressure

Π (MPa) is the difference of trans-membrane osmotic pressure

C_o and C_p denote feed average concentration and permeate concentration, respectively

Figure 6 shows a schematic representation of a membrane unit and the variables.

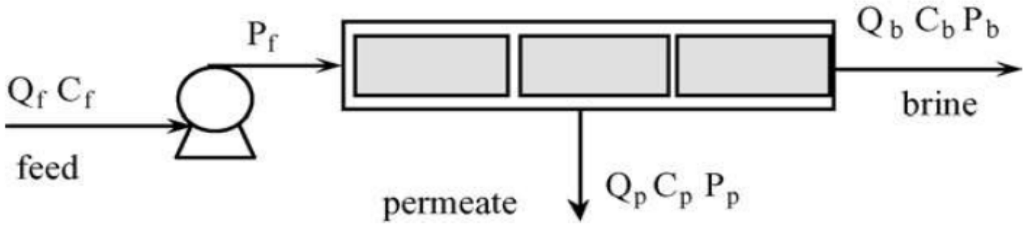

Figure 6. A schematic representation of a membrane unit and the variables [35].

The corresponding material balance relationships for a membrane unit are given by:

$$Q_f = Q_b + Q_p \quad (8)$$

$$Q_f C_f = Q_b C_b + Q_p C_p \quad (9)$$

Where: Q_f – feed stream flow rate, (m^3 h^{-1})

Q_b – brine stream flow rate, (m^3 h^{-1})

Q_p – permeate stream flow rate, (m^3 h^{-1})

C_f – feed stream concentration of solute (μlL^{-1})

The average feed flow rate per module (Q_f) is limited to avoid concentration polarization and excessive pressure drop. The pressure drop in the flow across each membrane unit is assumed to be constant. All these are usually specified by membrane manufactures [36].

$$Q^{fmin} \leq Q^f \leq Q^{fmax} \quad (10)$$

$$P_b = P_f - \delta P \quad (11)$$

Where: P_f – feed stream operating pressure (MPa)

P_b – brine stream operating pressure (MPa)

δP – trans-membrane pressure drop (MPa)

The water recovery rate, r, and the membrane salts rejection rate, R, are given by the following equations [20]:

$$r = \frac{Q_p}{Q_f} \quad (12)$$

$$R = 1 - \frac{C_p}{C_f} \quad (13)$$

Where: r – membrane water recovery rate (%),

Q_f – feed water flow rate, ($m^3\ h^{-1}$)

Q_p – permeate stream flow rate, ($m^3\ h^{-1}$)

R – rejection rate (%)

C_p – permeate salts mass concentration (kg of salts per kg of water)

C_f – feed salts mass concentration (kg of salts per kg of water)

Several techniques have been used in the mathematical modelling and optimization of RO systems. These include sequential quadratic programming (SQP) to determine the optimal networks of RO modules in a single objective function, multi-objective optimization (MOO) to simultaneously optimize several non-commensurate objective functions, and Genetic Algorithms (GAs) which have been widely used to solve optimization problems [37] (see for instance Figure 7). GAs are stochastic methods of search that imitate certain processes such as those of natural biological evolution. The application of GA solutions makes use of the survival of the fittest principle for better approximation solutions [38].

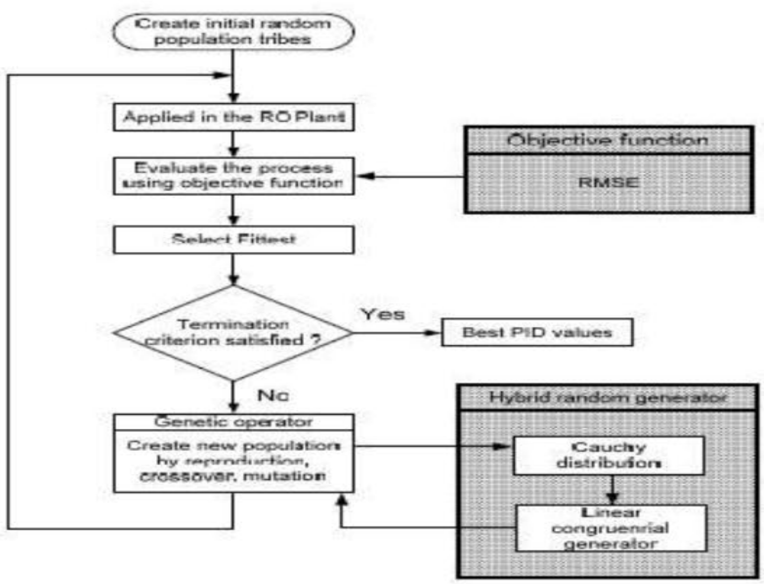

Figure 7. A flow-chart for a Genetic Algorithm with a hybrid random generator [41].

The final optimality solution using GA is not guaranteed and always encounters a couple of sub-optimal points/solutions. A more efficient multi-objective model, which is based on the lexicographic optimization and augmented epsilon constraint method, has been presented as an optimization technique substitute [39]. Economic optimization algorithms for RO have also been developed based on optimization algorithms for the calculation of water unit cost from various RO candidate schemes [40]. RO desalination units and plants generally require high levels of energy and therefore need fine-tuned mechanisms. Thus, to minimise or stabilise water production costs, designing a good control mechanism is necessary [41].

4. SIMULATIONS OF RO SYSTEMS

Below are the RO simulation equations in a RO unit [34].

1. Number of membranes in the unit, N_{mb}:

$$N_{mb} = \frac{Q_p}{f * S_{mb}} \quad (14)$$

2. Number of pressure tube vessels, N_{tp}:

$$N_{tp} = \frac{N_{mb}}{N_t} \quad (15)$$

3. Water product flow rate, Q_p:

$$Q_p = A * S_{mb} * TCF * FF * (\Delta P - \Delta \Pi) \quad (16)$$

4. Osmotic Pressure, Π:

$$\Pi = 0{,}002654 * (T + 273) * C * \frac{1}{1000 - \frac{C}{1000}} \quad (17)$$

5. Pressure drop between the feed and the brine, ∆P:

$$\Delta P = \left(P_f - \frac{1}{2}\Delta P_{fs}\right) \quad (18)$$

6. Pressure drop in a membrane, ΔP_{fs}:

$$\Delta P_{fs} = 0.01\bar{Q}_{fc}^{1.7} \quad (19)$$

7. Membrane Efficiency, k:

$$Y_k = 1 - (1 - Y)^{1/N_{mb}} \quad (20)$$

8. Salt product concentration, C_p:

$$C_p = (1 - R_{mb}) * C_{fc} * P_f * TCF * \frac{S_{mb}}{Q_p} \quad (21)$$

9. Charge conservation through the membrane, $Q_f C_f$:

$$Q_f C_f = Q_p C_p + Q_c C_c \quad (22)$$

10. Total volume of produced water, Q_T:

$$Q_T = \sum_{k-1}^{N_{mb}} Q_k \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (23)$$

11. Concentration of the produced water, C_T:

$$C_T = \frac{\sum_{k-1}^{N_{mb}} C_k Q_k}{Q_T} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (24)$$

12. Water permeability constant, K_w [32]:

$$K_w = \frac{J_w}{\Delta P - \Delta \Pi} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (25)$$

13. Gravimetric solute flux, Js [42]:

$$J_s = B\left(C_w - C_p\right) + (1-\sigma)J_w\bar{C} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (26)$$

Where:

$$\left(C_w - C_p\right) = \left(C_f - C_p\right)^{\frac{J_w}{k}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 27)$$

5. DESIGNS OF RO PLANTS

A large-scale RO plant is composed of a couple of modules (membrane elements). Some of the membrane modules deteriorate or malfunction because of aging and/or excessive fouling. These can be easily replaced. A number of RO membrane types with different characteristics have been developed and produced by the membrane manufacturers to suit different purposes, e.g. high flux membranes (for brackish water), high rejection membranes (for seawater) and fouling resistant membranes (suitable for feed waters leading to excessive fouling) [43]. Essential opportunities for reduction of cost are found in plant optimization designs and operation to use variable recovery, realize higher reliability through fail-safe designs and modularity, and reduce periodic, costly unplanned and unscheduled maintenance [22]. Power consumption by the RO system consists of high-pressure pumping (booster), and chemical treatment. The total power required is obtained by:

$$P_{W_n} = \frac{Q_n * P_{rn}}{E_n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (28)$$

Where:

- P_{wn} (kW) is the power consumed by feed, low-pressure, high-pressure and chemical water treatment pumps,
- Q_n (m^3/s) the rates of feed water ,
- P_{rn} (kPa) the feed pressure, and
- E_n (net efficiency of feed pump) [44].

The optimal design for RO desalination plants includes the material selection of membrane, geometry of the module (plate and frame, tubular, spiral-wound, or hollow-fiber), area of the membrane, product quality, solvent (water) recovery, operating pressure difference across the membrane, and the throughput. Scientists, engineers and economists have over the past years used AI-based techniques, particularly, GA for this purpose [45].

Figures 8-10 show different types of designs of RO desalination plants from a variety of scholars.

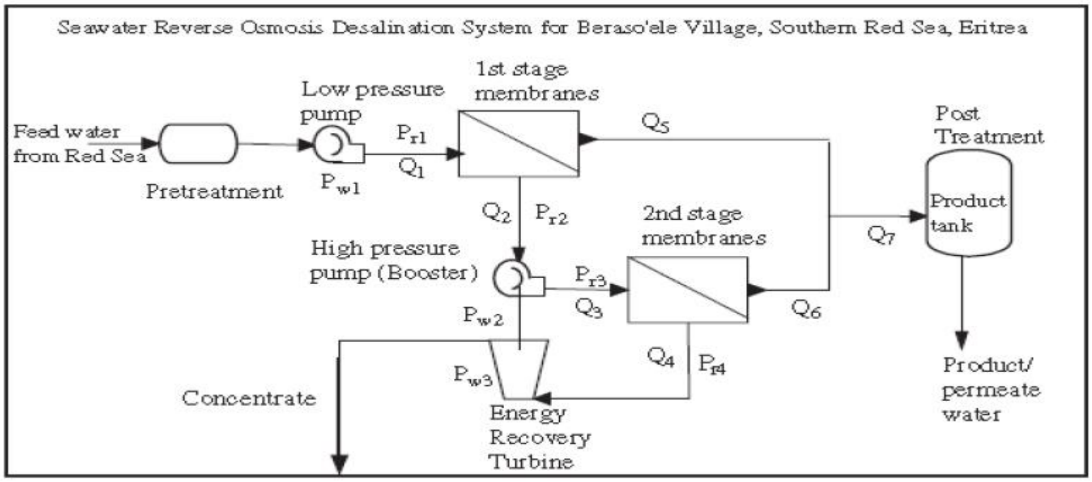

Figure 8. A schematic diagram of a two-stage RO system for the village of Bera'esoli, South-Eastern Red Sea, Eritrea [45].

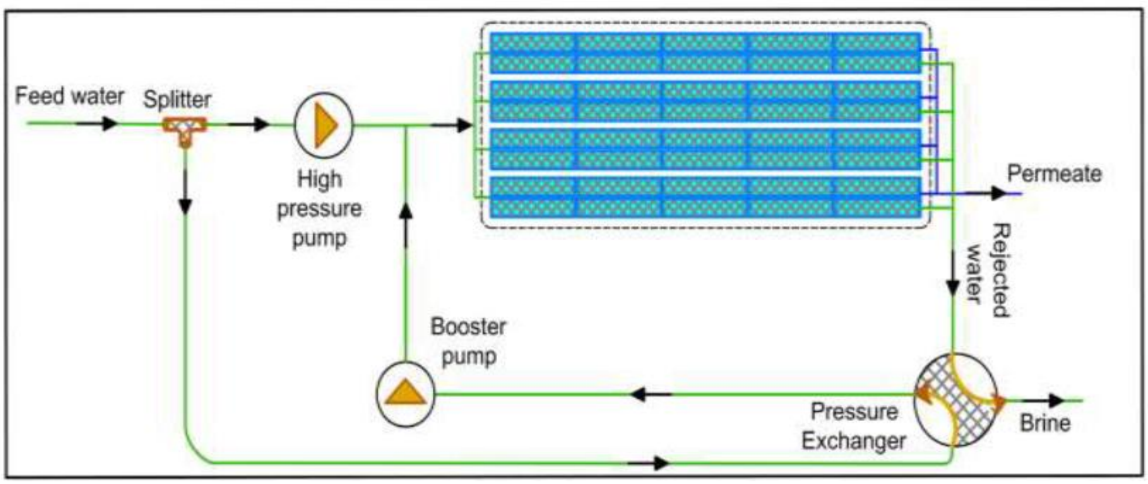

Figure 9. A RO plant schematic diagram [17].

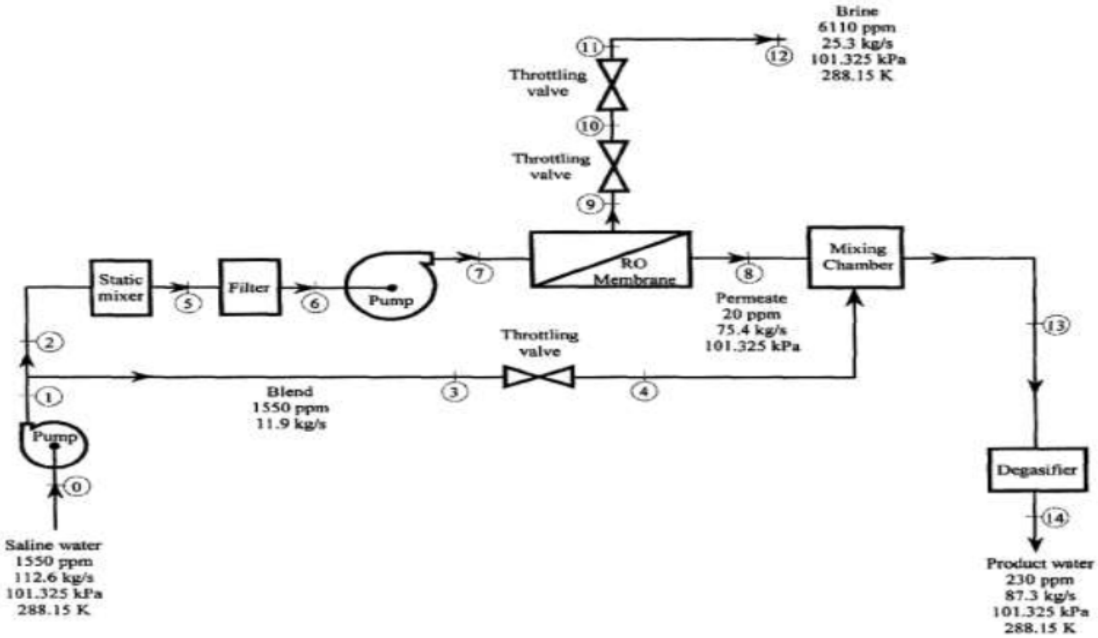

Figure 10. A Schematic diagram for a RO plant located in Oceanside, California, USA [46].

6. ENVIRONMENTAL IMPACTS OF RO DESALINATION

Projects for desalination should involve an environmental impact assessment (EIA) study to determine the environmental impact that the project can have. This study entails all environmental parameters and criteria. It also incorporates the evaluation of potential impacts and effects on air, land, and marine environments and at the same time recommends mitigation measures to reduce these impacts [47].

Environmental impacts pose quite a number of concerns when it comes to desalination technologies, mainly linked to the process of energy generation necessary for the operation of the desalination plant [48]. The generation of energy using fossil fuels for plant consumption may result in air pollution and dangerous gases like carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO2), and sulphur dioxide (SO2) emissions [49]. Waste water from desalination discharged into the marine environment may have a negative impact especially when it is released into sensitive ecosystems. These effects depend on the waste streams' physical-chemical properties and also the features, hydrographical and biological, of the receiving environment. Sites such as those which are shallow and enclosed habitats with abundant marine life are generally believed to be more sensitive to desalination waste discharges than the exposed, high energy, open-sea locations [50]. Table 3 summarises the predominant potential environmental pollutants during RO desalination.

Table 3. Potential environmental pollutants encountered in desalination plants [48].

Properties	RO Desalination
Concentrate salinity	Up to 65,000–80,000 mg/L
Temperature	Ambient seawater temperature
Dissolved oxygen (DO)	-If well intakes used, typically below ambient seawater DO -If open intakes used, approximately same as ambient seawater DO concentration
Chlorine (biofouling control)	If chlorine or other oxidants are used to control biofouling to prevent membrane damage, they typically are neutralized before water enters membranes
Coagulants (removal of TSS)	-May be present if source water is conditioned and filter backwash water not treated. -May cause effluent coloration if not equalized prior to discharge
Anti-scalants (scale control)	Typically, below toxic levels
Antifoaming agents (foam control)	Not present
Heavy metals (contaminants due to corrosion)	Traces of iron, chromium, nickel, and molybdenum if low-quality materials are used
Cleaning chemicals	Alkaline or acidic solutions with additives, complexing agents, oxidants, and biocides

7. CONCLUSION

The supply of potable water has always been an issue to be resolved the world over. Reverse osmosis desalination and the study of the technologies involved will continue to be improved until a more effective and efficient method is designed. Different scholars have determined that improvements and development of robust and self-cleaning membranes like carbon nanotubes can help reduce the cost of water production significantly but will increase the setup costs compared to the general cellulose membranes. Optimization and modeling of the system using several methods have been also developed and the use of techniques such as GA has been incorporated. These have significantly improved the efficiency of the system. Continuous improvement and study is still needed regarding the membrane modules to be used, and the energy required to reduce the generally high energy consumption of the system. This will increase the production of potable water at lower costs, and at the same time increase the efficiency of the system.

ACKNOWLEDGEMENTS

NOMENCLATURE

C - salt concentration (ppm)

J - flux through the membrane,

f - pure water transport coefficient (m^3/m^2 mn)

FF - membrane fouling factor (0.8 à 1)

N - number of units

P_f - concentration polarization factor

Q - flow rate (m^3/s)

S - surface (m^2)

T - temperature (^oC)

TCF - temperature correction factor (%)

Y - system recovery fraction

Y_k - recovery fraction for Membrane k supposed the same for all the membranes

ΔP - applied transmembrane pressure (Pa)
$\Delta \Pi$ - transmembrane osmotic pressure (Pa)
ΔP_{fs} - transmembrane pressure drop (Pa)
B - solute permeability coefficient (m/day);
$\bar{C}$ - arithmetic average of concentration of solute across the membrane phase (kg/m3);
k - mass transfer coefficient (m/day).

INDICES

c - concentrate, brine.
f - feed water
fc - average flux between feed and concentrate
k - the element k (PV, membrane)
m - average
mb - membrane
p - membrane permeate, product
t - membrane in pressure vessel
tp - pressure vessel
T - total of permeate water

REFERENCES

[1] Rijsberman, F. R. Water Scarcity: Fact or Fiction. *Agricultural Water Management,* 80, 2006, pp. 5-22. https://doi.org/10.1016/j.agwat.2005.07.001

[2] Shaffer, D. L., Yip, N. Y., Gilron, J. and Elimelech, M. Seawater Desalination for Agriculture by Integrated Forward and Reverse Osmosis: Improved Product Water Quality for Potentially Less Energy. *Journal of Membrane Science,* 415, 2012, pp. 1-8. https://doi.org/10.1016/j.memsci.2012.05.016

[3] Blignaut J. and Van Heerden, J. The Impact of Water Scarcity on Economic Development Initiatives. *Water SA.* 35, 2009. http://dx.doi.org/10.4314/wsa.v35i4.76800

[4] Goosen, M., Sablani, S., Al-Hinai, H., Al-Obeidani, S., Al-Belushi, R. and Jackson, A. Fouling of Reverse Osmosis and Ultrafiltration Membranes: A Critical Review, *Separation Science and Technology,* 39, 2005, pp. 2261-2297. https://doi.org/10.1081/SS-120039343

[5] Matin, A., Khan, Z., Zaidi, S. and Boyce, M. Biofouling in Reverse Osmosis Membranes for Seawater Desalination: Phenomena and Prevention. *Desalination,* 281, 2011, pp. 1-16, 2011. https://doi.org/10.1016/j.desal.2011.06.063

[6] Duan, J., Pan, Y., Pacheco, F., Litwiller, E., Lai, Z. and Pinnau, I. High-Performance Polyamide Thin-Film-Nanocomposite Reverse Osmosis Membranes Containing Hydrophobic Zeolitic Imidazolate Framework-8. *Journal of Membrane Science,* 476, 2015, pp. 303-310. https://doi.org/10.1016/j.memsci.2014.11.038

[7] Tularam G. A. and Ilahee, M. Environmental Concerns of Desalinating Seawater Using Reverse Osmosis. *Journal of Environmental Monitoring,* 9, 2007, pp. 805-813. DOI: 10.1039/B708455M

[8] Lee, T., Rahardianto, A. and Cohen, Y. Flexible Reverse Osmosis (FLERO) Desalination. *Desalination,* 452, 2019, pp. 123-131. https://doi.org/10.1016/j.desal.2018.10.022

[9] Shatat M. and Riffat, S. B. Water Desalination Technologies Utilizing Conventional and Renewable Energy Sources. *International Journal of Low-Carbon Technologies,* 9, 2012, pp. 1-19. https://doi.org/10.1093/ijlct/cts025

[10] Ghaffour, N., Missimer, T. M. and Amy, G. L. Technical Review and Evaluation of the Economics of Water Desalination: Current and Future Challenges for Better Water Supply Sustainability *Desalination,* 309, 2013, pp. 197-207. https://doi.org/10.1016/j.desal.2012.10.015

[11] Voutchkov, N. *Desalination Engineering: Planning and Design*: McGraw Hill Professional, 2012.

[12] Islam, M., Sultana, A., Saadat, A., Shammi, M. and Uddin, M. Desalination Technologies for Developing Countries: A Review *Journal of Scientific Research,* 10, 2018, pp. 77-97. https://doi.org/10.3329/jsr.v10i1.33179

[13] Al-Zahrani, A., Orfi, J., Al-Suhaibani, Z., Salim, B. and Al-Ansary, H. Thermodynamic Analysis of a Reverse Osmosis Desalination Unit with Energy Recovery System. *Procedia Engineering,* 33, 2012, pp. 404-414. https://doi.org/10.1016/j.proeng.2012.01.1220

[14] Raval H. D. and Gohil, J. M. Carbon Nanotube Membrane for Water Desalination, *International Journal of Nuclear Desalination,* 3, 2009, pp. 360-368. DOI: 10.1504/IJND.2009.028863

[15] Atab, M. S., Smallbone, A. and Roskilly, A. An Operational and Economic Study of a Reverse Osmosis Desalination System for Potable Water and land irrigation, *Desalination,* 397, 2016, pp. 174-184. https://doi.org/10.1016/j.desal.2016.06.020

[16] Jiang, A., Ding, Q., Wang, J., Jiangzhou, S., Cheng, W. and Xing, C. Mathematical Modeling and Simulation of SWRO Process Based on Simultaneous Method. *Journal of Applied Mathematics,* 2014, 2014. http://dx.doi.org/10.1155/2014/908569

[17] Atab, M. S., Smallbone, A. and Roskilly, A. A Hybrid Reverse Osmosis/Adsorption Desalination Plant for Irrigation and Drinking Water, *Desalination,* 444, 2018, pp. 44-52, https://doi.org/10.1016/j.desal.2018.07.008

[18] Malaeb L. and Ayoub, G. M. Reverse Osmosis Technology for Water Treatment: State of the Art Review. *Desalination,* 267, 2011, pp. 1-8. https://doi.org/10.1016/j.desal.2010.09.001

[19] Madaeni, S. and Koocheki, S. Application of Taguchi Method in the Optimization of Wastewater Treatment Using Spiral-Wound Reverse Osmosis Element. *Chemical Engineering Journal,* 119, 2006, pp. 37-44. https://doi.org/10.1016/j.cej.2006.03.002

[20] Vince, F., Marechal, F., Aoustin, E. and Bréant, P. Multi-Objective Optimization of RO Desalination Plants, *Desalination,* 222, 2008, pp. 96-118. https://doi.org/10.1016/j.desal.2007.02.064

[21] Das, R., Ali, M. E. Hamid, S. B. A, Ramakrishna, S. and Chowdhury, Z. Z. Carbon Nanotube Membranes for Water Purification: A Bright Future in Water Desalination. *Desalination,* 336, 2014, pp. 97-109. https://doi.org/10.1016/j.desal.2013.12.026

[22] Peñate, B. and García-Rodríguez, L. Current Trends and Future Prospects in the Design of Seawater Reverse Osmosis Desalination Technology. *Desalination,* 284, 2012, pp. 1-8. https://doi.org/10.1016/j.desal.2011.09.010

[23] Johnson J. and Busch, M. Engineering Aspects of Reverse Osmosis Module Design. *Desalination and Water Treatment,* 15, 2010pp. 236-248. https://doi.org/10.5004/dwt.2010.1756

[24] Sundaramoorthy, S., Srinivasan, G. and Murthy, D. Reprint of: "An Analytical Model for Spiral Wound Reverse Osmosis Membrane Modules: Part II—Experimental Validation". *Desalination,* 280, 2011, pp. 432-439. https://doi.org/10.1016/j.desal.2011.04.037

[25] Bodalo-Santoyo, A., Gomez-Gomez, E., Maximo-Martin, M. and Hidalgo-Montesinos, A. Spiral-Wound Membrane Reverse Osmosis and the Treatment of Industrial Effluents. *Desalination,* 160, 2004, pp. 151-158. https://doi.org/10.1016/S0011-9164(04)90005-7

[26] Han, K.-B., Kim, S. and Choi, Y. Desalination Property of Pure Multi-Walled Carbon Nanotubes. *International Journal of Applied Engineering Research,* 11, 2016, pp. 8946-8948.

[27] Sears, K., Dumée, L., Schütz, J., She, M., Huynh, C., Hawkins, S. *et al*. Recent Developments in Carbon Nanotube Membranes for Water Purification and Gas Separation. *Materials,* 3, 2010, pp. 127-149. doi: 10.3390/ma3010127

[28] Weinrich, L., Haas, C. N. and LeChevallier, M. W. Recent Advances in Measuring and Modeling Reverse Osmosis Membrane Fouling in Seawater Desalination: A Review. *Journal of Water Reuse and Desalination,* 3, 2013, pp. 85-101. https://doi.org/10.2166/wrd.2013.056

[29] Pangarkar, B. L., Sane, M. G. and Guddad, M. Reverse Osmosis and Membrane Distillation for Desalination of Groundwater: A Review. *ISRN Materials Science,* 2011, 2011. http://dx.doi.org/10.5402/2011/523124

[30] Qin, J.-J., Liberman, B. and Kekre, K. A. Direct Osmosis for Reverse Osmosis Fouling Control: Principles, Applications and Recent Developments. *The Open Chemical Engineering Journal,* 3, 2009, pp. 8-16. DOI: 10.2174/1874123100903010008

[31] Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B. and Moulin, P. Reverse osmosis Desalination: Water Sources, Technology, and Today's Challenges, *Water Research,* 43, 2009, pp. 2317-2348. https://doi.org/10.1016/j.watres.2009.03.010

[32] Barello, M., Manca, D., Patel, R. and Mujtaba, I. M. Neural Network Based Correlation for Estimating Water Permeability Constant in RO Desalination Process under Fouling. *Desalination,* 345, 2014, pp. 101-111. https://doi.org/10.1016/j.desal.2014.04.016

[33] Khayet, M. Cojocaru, C. and Essalhi, M. Artificial Neural Network Modeling and Response Surface Methodology of Desalination by Reverse Osmosis. *Journal of Membrane Science,* 368, 2011, pp. 202-214. https://doi.org/10.1016/j.memsci.2010.11.030

[34] Bourouni, K., M'Barek, T. B. and Al Taee, A. Design and Optimization of Desalination Reverse Osmosis Plants Driven by Renewable Energies using Genetic Algorithms, *Renewable Energy,* 36, 2011, pp. 936-950. https://doi.org/10.1016/j.renene.2010.08.039

[35] Lu, Y.-Y., Hu, Y.-D., Zhang, X.-L., Wu, L.-Y. and Liu, Q.-Z. Optimum Design of Reverse Osmosis System under Different Feed Concentration and Product Specification. *Journal of Membrane Science,* 287, 2007, pp. 219-229. https://doi.org/10.1016/j.memsci.2006.10.037

[36] Lu, Y.-y., Hu, Y.-d., Xu, D.-m. and Wu, L.-y. Optimum Design of Reverse Osmosis Seawater Desalination System Considering Membrane Cleaning and Replacing. *Journal of Membrane Science,* 282, 2006, pp. 7-13, 2006. https://doi.org/10.1016/j.memsci.2006.04.019

[37] Murthy Z. and Vengal, J. C. Optimization of a Reverse Osmosis System Using Genetic Algorithm. *Separation Science and Technology,* 41, 2006, pp. 647-663. https://doi.org/10.1080/01496390500526854

[38] Djebedjian, B., Gad, H., Khaled, I. and Rayan, M. A. Optimization of Reverse Osmosis Desalination System Using Genetic Algorithms Technique. In: *Twelfth International Water Technology Conference, IWTC12, Alexandria, Egypt*, 2008.

[39] Du, Y., Xie, L., Liu, J., Wang, Y., Xu, Y. and Wang, S. Multi-Objective Optimization of Reverse Osmosis Networks by Lexicographic Optimization and Augmented Epsilon Constraint Method. *Desalination,* 333, 2014, pp. 66-81. https://doi.org/10.1016/j.desal.2013.10.028

[40] Poullikkas, A. Optimization Algorithm for Reverse Osmosis Desalination Economics. *Desalination,* 133, 2001, pp. 75-81. https://doi.org/10.1016/S0011-9164(01)00084-4

[41] Kim, J.-S., Kim, J.-H., Park, J.-M., Park, S.-M., Choe, W.-Y. and Heo, H. Auto Tuning PID Controller Based on Improved Genetic Algorithm for Reverse Osmosis Plant. *World Academy of Science, Engineering and Technology,* 47, 2008, pp. 384-389.

[42] Park, P.-K., Lee, S., Cho, J.-S. and Kim, J.-H. Full-Scale Simulation of Seawater Reverse Osmosis Desalination Processes for Boron Removal: Effect of Membrane Fouling. *Water Research,*.46, 2012, pp. 3796-3804. https://doi.org/10.1016/j.watres.2012.04.021

[43] Abbas A. and Al-Bastaki, N. Modeling of an RO Water Desalination Unit Using Neural Networks. *Chemical Engineering Journal,* 114, 2005, pp. 139-143. https://doi.org/10.1016/j.cej.2005.07.016

[44] Gilau A. M. and Small, M. J. Designing cost-Effective Seawater Reverse Osmosis System Under Optimal Energy Options. *Renewable Energy,* 33, 2008, pp. 617-630. https://doi.org/10.1016/j.renene.2007.03.019

[45] Guria, C., Bhattacharya, P. K. and Gupta, S. K. Multi-Objective Optimization of Reverse Osmosis Desalination units Using Different Adaptations of the non-dominated sorting genetic algorithm (NSGA). *Computers & Chemical Engineering,* 29, 2005, pp. 1977-1995. https://doi.org/10.1016/j.compchemeng.2005.05.002

[46] Cerci, Y. Exergy Analysis of a Reverse Osmosis Desalination Plant in California. *Desalination,* 142, 2002, pp. 257-266. https://doi.org/10.1016/S0011-9164(02)00207-2

[47] Berktay, A. Environmental Approach and Influence of Red Tide to Desalination Process in the Middle East Region, *International Journal of Chemical and Environmental Engineering,* 2, 2011.

[48] Miller, S., Shemer, H. and Semiat, R. Energy and Environmental Issues in Desalination. *Desalination,* 366, 2015, pp. 2-8. https://doi.org/10.1016/j.desal.2014.11.034

[49] Younos, T. Environmental Issues of Desalination. *Journal of Contemporary Water Research and Education,* 132, 2005, p. 3.

[50] Lattemann S. and Höpner, T. Environmental impact And Impact Assessment of Seawater Desalination. *Desalination,* 220, 2008, pp. 1-15. https://doi.org/10.1016/j.desal.2007.03.009

CHAPTER 3. Sea-water Reverse Osmosis Desalination: Energy and Economic Analysis

This chapter outlines the energy and economic analysis of seawater reverse osmosis. This includes the factors that affect the operation of the plant, energy consumption of already operating plants and the investment required to operate the plants. This article was published in the International Journal of Mechanical Engineering and Technology (IJMET).

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SEA WATER REVERSE OSMOSIS DESALINATION: ENERGY AND ECONOMIC ANALYSIS

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ABSTRACT

Sea water desalination is a process that separates saline water into two major components, the low dissolved salts concentration water stream (fresh or potable water) and the high dissolved salts concentration water, using several generally high energy and cost mechanisms. Reverse Osmosis (RO) is currently the most widely used technology owing to its continuous improvement in membrane technology and energy consumption rates, thereby increasing the throughput and efficiency of the technology. These improvements have led to a dramatic reduction of both the capital and the operational costs. Studies on reduction of energy consumption in desalination have been one of the major priorities in recent years and the results have been very significant. The incorporation of energy recovery devices has also led to major benefits in the technology as some of the energy is recycled for productive use. Research and development of energy and cost effective desalination technologies is an ongoing process as sources of fresh water continue to diminish at an alarming rate while at the same time the population growth is increasing dramatically. In this regard, RO has become the most viable technology in desalination. This paper seeks to analyze the effects of energy and costs of RO desalination technology.

Keywords: Desalination, reverse osmosis, energy.

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1. INTRODUCTION

The provision of potable and fresh water is becoming an extremely important issue worldwide. Potable water is very scarce in arid areas and the establishment of human habitats in such areas strongly hinge on how such water can be made available [1]. Reverse osmosis (RO) has become the most commonly used and preferred desalination technology world-wide. With the rise in population and the increased demand for potable water there is a great need to come up with lasting solutions [2]. Between 2008 and 2013 global desalination capacity grew by 57%. This movement is expected to continue for the following main reasons: population growth, traditional water resources are diminishing, and advances in membrane technology. Seawater desalination is a major contributor, with about 59% of global desalination capacity attributed to it [3]. One of the major significant costs in the economics of desalination of water is energy costs, but the insufficiency of water is motivating the rapid growth and development of desalination facilities worldwide. Non-renewable conventional fossil fuels have been exploited as the main source of energy, but excessive emission of greenhouse gases, leading to global warming, has encouraged worldwide development and implementation of minimal energy use strategies and green energy supplies. Several advancements of RO technology have occurred recently and research continues to be carried out to improve this process [4].

2. ENERGY CONSUMPTION IN DESALINATION

Energy is a critical factor for socio-economic development and is also an important need in industrial growth, as is quality water [5]. Water and energy are two inseparable commodities that govern the lives of humanity and promote civilization [1]. The progression of desalination plants in 30 years of experience related to energy consumption of large seawater desalination plants is shown in Figure 1 [6].

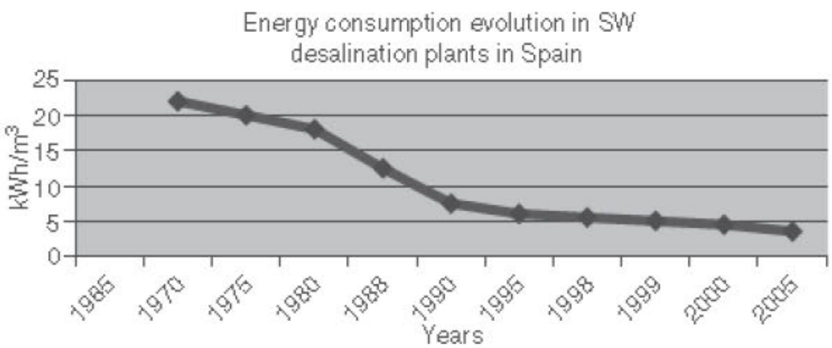

Figure 1 Energy consumption evolution in Seawater desalination plants in Spain [6]

Usage of renewable energy sources has been implemented in recent years but renewable sources have proven to have their own inherent disadvantages, including technological shortcomings and capital intensive installation costs. Energy source and energy efficiency needs to be considered in designing desalination systems as well as renewable sources and sustainability, therefore having in place the related infrastructure required to integrate advanced desalination solutions is important [5]. The amount of energy (thermal and/or electrical) needed for a desalination plant depends on the technology used. Table 1 shows the typical values required for the production of 1 m^3 of water exclusive of the water transport [7].

Table 1 Typical energy requirements for different desalination techniques [7]

Process	Thermal Energy (kWh/m^3)	Electrical Energy (kWh/m^3)	Comments
MFS	12	3.5	Feed steam > 110 °C
MED	6	1.5	Can operate at < 70 °C
RO	-	4 - 7	

Note: MFS – Multi-stage flash distillation; MED – Multi-effect distillation.

The only form of energy required in the RO process is electrical energy. A number of factors affect the energy consumption of the RO unit. One major factor is the salinity of feed water and the recovery rate of the system. Feed water with high-salinity requires a higher amount of energy owing to higher osmotic pressure. Osmotic pressure is associated with the concentration of total dissolved solids (TDS) of the feed water. RO units vary in size from very small units with a capacity of 0.1 m^3/day to very large units with a capacity of 395 000 m^3/day. The average energy consumption reported ranges from 3.7 kWh/m^3 to 8 kWh/m^3. The consumption may surpass 15 kWh/m^3 for very small unit sizes [8]. Several aspects such as process design, energy recovery system, waste water disposal system, quality of desalinated water, and the type of membrane, affect energy consumption [9].

The leading factors in minimization of energy usage in RO desalination processes can be categorized as follows: enhanced system design, energy recovery, high efficiency pumping, innovative technologies, and advanced membrane materials [4]. Figure 2 shows the various components of an RO system and their respective energy usage [10].

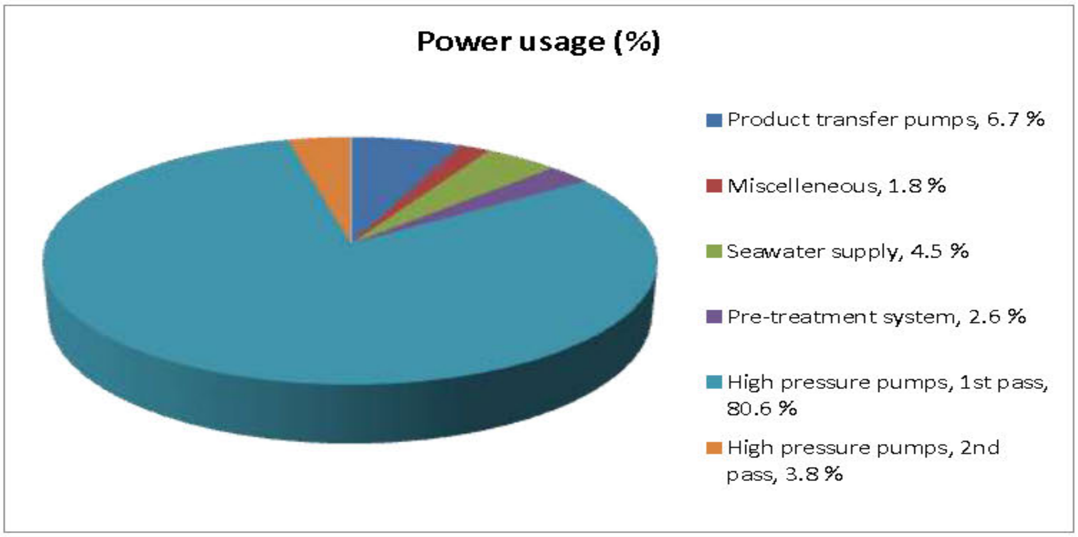

Figure 2 Different components and their power usage in a RO [10].

In order to grasp RO energy usage, it is important to understand the concept of osmosis and osmotic pressure. RO is a process whereby a membrane separates two solutions of different salinities so that potable water moves to the region with low saline concentration and the molecules with high saline concentration move to the other side of the membrane. Because there is a blockage in solute movement, momentum is transferred to the membrane. The exerted pressure on the surface of the membrane is referred to as osmotic pressure. To produce pure water from salty water, there must be a reversal of the natural osmotic flow. This is reached by applying a force externally on the solution with higher salinity, resulting in pressure which is greater than the osmotic pressure. Therefore, the minimum pressure necessary to produce potable water from saline water is equal to the osmotic pressure if there is no resistance to the flow of water offered by the membrane. The osmotic pressure can be calculated using Van't Hoff's equation as shown in Eq. (1) [11]:

$$\Pi = cRT \tag{1}$$

Where:
Π – Osmotic pressure,
c – Molar solute concentration,
R – Gas constant, and
T – Absolute temperature.

The total energy requirement for the running of an entire RO desalination plant is given by Eq. (2):

$$E_T = E_{in} + E_{pt} + E_{hp} + E_A - E_{ERD} \quad (2)$$

Where:
E_T – Total energy requirement,
E_{in} – Energy required to draw the feed water from the source,
E_{pt} – Energy required for pre-treatment and post-treatment (micro filtration and pumping),
E_{hp} – Energy required by the high-pressure pump,
E_A – Energy required by other accessories (chemical dosing, filter backwashing/cleaning and pumping the product water), and
E_{ERD} – Energy recovered by the energy recovery device (ERD) [12].

Specific energy consumption (SEC), which describes the amount of electrical energy required to produce one cubic metre of permeate, can be used to evaluate the energy costs of an RO plant. Ideally, assuming 100 % pump efficiency, work done by the pump is assumed to be equal to the electrical energy required, as given by Eq. (3):

$$SEC = \frac{W_{pump}}{Q_p} \quad (3)$$

Where:
Q_p – Permeate flow rate,
W_{pump} – Rate of work done by the pump, which is given by Eq. (4):

$$W_{pump} = \Delta P * Q_f \quad (4)$$

In which,

$$\Delta P = P_f - P_o \quad (5)$$

Where:
P_f – Feed pressure at the entrance of the membrane module,
P_o – Pressure of the raw water,
Q_f – Volumetric Feed Flow rate [13].

Consequently, for a given recovery system for a single stage RO process that operates up to a certain thermodynamic restriction limit, the optimal SEC, also known as the normalised SEC (SEC_{norm}), can be expressed as Eq. 6:

$$SEC_{norm} = \left[\frac{1 - \eta_{ERD}(1 - Y)}{Y(1 - Y)}\right]\left[\frac{R}{\eta_{pump}}\right] \quad (6)$$

Where:
η_{ERD} and η_{pump} – efficiencies of energy recovery devices and pump respectively,
R – Membrane salt rejection,

Y – Permeate recovery, and is given by Eq. (7):

$$Y = \frac{Q_p}{Q_f} \quad (7)$$

Normalised SEC_{norm} is defined as $SEC_{norm} = SEC/\pi_0$, where π_0 is the RO feed osmotic pressure [14].

The approach for a single stage RO operation can easily be applied and extended for a multiple stage RO process. For a simple two-stage RO configuration, the overall water recovery, Y, is given by the result of the recoveries at the first and second stage, Y_1 and Y_2, by application of the simple mass balance as shown by Eq. (8):

$$Y = Y_1 + (1 - Y_1)Y_2 = Y_1 + Y_2 - Y_1Y_2 \quad (8)$$

Assuming 100 % pump efficiency, the rate of work done at the first stage, where thermodynamic restrictions apply is given by Eq. (9):

$$W_{tr}^{1st} = \left[\frac{\pi_0}{1 - Y_1}\right] Q_f \quad (9)$$

Likewise, the rate of work done at the second stage, where thermodynamic restrictions apply is given by Eq. (10):

$$W_{tr}^{2nd} = \left[\frac{\pi_0}{1 - Y} - \frac{\pi_0}{1 - Y_1}\right] Q_f(1 - Y_1) \quad (10)$$

Therefore, the normalised SEC for the two stage RO process at the thermodynamic restriction is given by Eq. (11) [15]:

$$SEC_{tr,norm}(2RO) = \frac{W_{tr}^{1st} + W_{tr}^{2nd}}{YQ_f\pi_0} = \frac{1}{Y}\left[\frac{1}{1 - Y_1} + \frac{1 - Y_1}{1 - Y} - 1\right] \quad (11)$$

Understanding the minimum amount of energy required to separate pure water from seawater provides a standard for comparison and can help to guide future efforts to further reduce energy demand. This minimum energy (theoretical), which is independent of the desalination method, is realized when the separation occurs as a reversible thermodynamic process. As a result, the magnitude of energy required for separation will be equal and opposite in sign to the free energy of mixing. The relationship between the osmotic pressure and the free energy of mixing is given by Eq. (12) [16]:

$$-d(\Delta G_{mix}) = -RT \ln a_w dn_w = \Pi_s \bar{V}_w dn_w \quad (12)$$

Where:

ΔG_{mix} – Free energy of mixing,

R – Ideal gas constant,

T – Absolute temperature,

a_w – Activity of water,

n_w – Number of moles of water,

Π_s – Osmotic pressure of the seawater, and

V_w – Molar volume of water.

One of the major consumers of energy in the process of seawater RO (SWRO) is the feed pump itself. To achieve maximum possible efficiency, a pump curve typically shows that the specific speed should be within a specified range for optimal efficiency. Specific speed, n_q, is defined by Eq. (13) [11]:

$$n_q = \frac{n * Q^{0.5}}{H^{0.75}} \quad (13)$$

in which:
n – Speed of the pump,
Q – Flow rate,
H – Total dynamic head.

For optimal energy, n_q should be greater than 900 [11].

2.1. Energy Recovery in RO Systems

The RO desalination process is energy intensive. This is due to the low recovery ratio (25 % to 40 %) and the high operating pressure (60 bar to 80 bar) [17]. A crucial condition for the layout of an RO system is the specific energy consumption, which should be kept as low as possible. This, therefore, means that the recovery ratio must be as high as possible and the associated feed water pressure be kept as low as possible without compromising the standards of the quality of water produced. For this reason, most, if not all, of the large and small scale seawater RO plants are fitted with energy-recovery turbines that help recover some of the pumping energy as shown in Figure 3 [18].

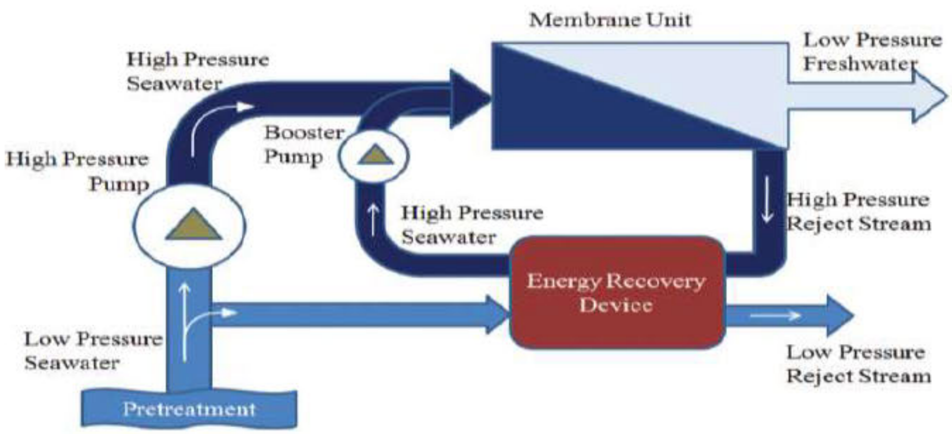

Figure 3 RO plant with an energy recovery device [12]

Energy recovery devices (ERDs) are the components used to reduce energy consumption for RO desalination processes and this has been shown to recover the energy from the RO concentrate stream. The pressure from the concentrate stream is recovered by passing it through an ERD before the concentrate is sent for disposal. The efficiency of the system determines the fraction of power recovered.

ERDs are classified into two broad classes: Class I devices which use hydraulic power in a one step process to cause a positive displacement within the recovery device, and Class II devices which use the hydraulic energy of the RO concentrate that first converts this energy to centrifugal mechanical energy and then back to hydraulic energy in a two-step process. ERD are used by most RO plants today [4]. The positive displacement based devices are pressure and work exchangers. This type contributes to a higher energy recovery efficiency (ERE) of between 90 % and 95 %, compared to the turbine type, which has an ERE of between 50 % and 90 %. Positive displacement based devices have a more promising and competitive technology in the field of desalination [12].

Over the past decade, the specific energy for RO desalination has significantly reduced and is gradually approaching the theoretical thermodynamic minimum. The development of large pumps with energy recovery devices has led to this significant energy reduction. These devices, known as "turbochargers", "pressure exchangers", or "work exchangers" represent efficient ways of energy recovery content of the high-pressure concentrate leaving the membrane module. These turbines convert the pressure from the concentrate into a high speed jet that rotates a wheel. This is either used to decrease the power consumed by the driving motor of the pump or to boost the pressure of the feed to a second stage since the salt concentration will be higher in the second stage than in the first stage [19, 20]. For a 24 000 m^3/day sea water RO unit, the electricity consumption ranges from 4 kWh/m^3 to 6 kWh/m^3 when an energy recovery system is included. Desalination of brackish water requires low pressures; therefore, different types of membranes are used. This will result in much higher recovery ratios, which will significantly reduce energy consumption. For a brackish-water RO unit, the consumption of electrical energy ranges from 1.5 kWh/m^3 to 2.5 kWh/m ^{3} [8]. Several ERDs have been employed in the desalination process. These include the high efficiency hydraulic energy recovery (HER) and the osmotic energy recovery (OER) devices. HER devices are responsible of transferring hydraulic energy to a low-pressure feed stream from a high pressure brine stream prior to its discharge. OER devices employ the partial recovery of chemical potential energy (the same energy used in the separation of potable water from saline water) from the concentrated brine [21]. The power retrievable from the energy recovery system is related to its capacity as in Eq. (14) [22]:

$$W_{ers} = \eta_{ers} P_r Q_{rt} \tag{14}$$

Where:

W_{ers} – Work done by the energy recovery system,

η_{ers} – Efficiency of the energy recovery systems (approximately constant at 0.67).

P_r – Pressure from the reject stream (bars),

Q_{rt} – total reject flow rate from the RO plant (m^3/d).

3. ECONOMICS AND COSTS ASSOCIATED WITH RO DESALINATION

The costs of desalination differ considerably from one geographic location to another. Costs are affected by geographical, socio-economic and environmental conditions as well as protocols regarding construction and operation desalination plants. Therefore, comparing of desalination costs between different regions directly is complicated and not recommended [23]. Economic analysis is the most effective factor that determines the applicability of RO desalination systems [24]. There are many factors that affect the economics of desalination. These factors include the following: intake water quality, energy cost, plant capital cost, year of construction of the plant, maintenance cost, labour costs, cost of disposal of the concentrate, region where the plant is installed and financing interest rate [8, 25]. The largest sector of water production cost of all desalination systems is energy cost [8]. There are several cost technologies that have been studied and one such technology is VARI-RO "Low Energy" technology (VRO). This is a variable flow, positive displacement pumping, energy recovery, and energy conversion system for the RO desalination of brackish water (BWRO) and seawater (SWRO) [26]. Costs of energy related to stand-alone desalination plants can range from 30 % to 50 % of the potable water production costs [7]. The operation and maintenance costs usually range from around 15 % to 30 % of the total water production cost, depending on size of the plant and process design [27]. The cost of desalted water supplied to consumers decreased from around \$2.0/m^3 in 1998 to a price of about \$0.5/m^3 in the past 5 years. Chief drivers behind this economic improvement have been high competition and improved membrane technologies. A pie-chart of the components costs (from the year 2002) of an RO desalination plant is shown in Figure 4 [10].

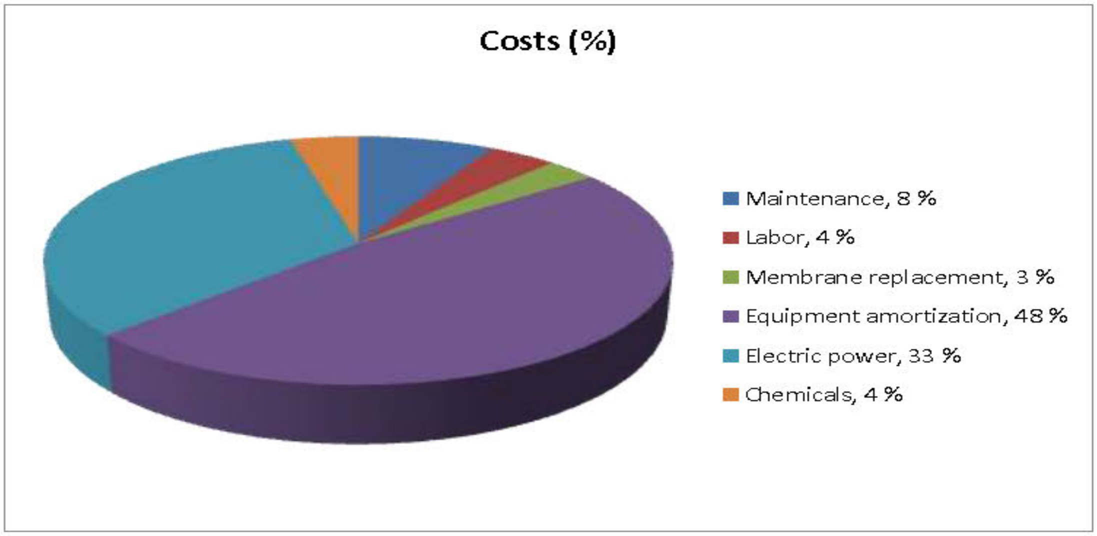

Figure 4 Costs associated with RO desalination plants [10].

The power law rule is normally used to calculate the capacity-cost relationship in engineering. For a plant of known capacity, this law can be used to calculate the capital cost of a new plant based on the known capital costs of an existing plant as shown in Eq. (15) [28].

$$\frac{Capital\ Cost_{Plant\ 1}}{Capital\ Cost_{Plant\ 2}} = \frac{Plant\ Capacity_{Plant\ 1}}{Plant\ Capacity_{Plant\ 2}} \quad (15)$$

Capital cost refers to the total of all start-up costs, which include land, construction and infrastructure costs necessary to have the plant operative using the market price. Plant capacity means the potential desalinated water volume produced per day taking into consideration the current facilities and available equipment [9].

Several scholars have come up with different methodologies for calculation of the costs of running a desalination plant. Some of the methodologies are well established and can apply to different kinds of industries. The commonly used indicator in the investment evaluation is the net present value (NPV) and the energy related operation costs ($C_{E,t}$) which can be calculated using Eqs (16) and (17) respectively [25]:

$$NPV = \sum_{t=1}^{n} \frac{R_t - C_t}{(1+i)^t} - I_o \quad (16)$$

$$C_{E,t} = E_{El,t} * P_{El,t} + E_{th,t} * P_{th,t} \quad (17)$$

Where:

I_o – Initial capital investment,

i – Appropriate discount rates,

n – Number of years,

R_t – Revenue in year t,

C_t – Costs in year t,

$E_{El,t}$ – Amount of electrical energy used by the plant in year t,

$E_{th,t}$ – Amount of thermal energy used by the plant in year t,
$P_{El,t}$ – Cost of unit electrical energy used by the plant in year t,
$P_{th,t}$ – Cost of unit thermal energy used by the plant in year t.

In desalination projects, the R_t represents the revenues collected from selling the water produced; therefore, NPV calculation entails the assessment of the amount of water produced and the price at which the water can be sold at the point of production from year 1 to year n [25].

3.1. Total Cost of Ownership (TCO) for Desalination

The total cost of ownership (TCO) of a desalination plant is the cost being calculated over the plant's life cycle. This can either be the contract period of a project (typically 20 years) or the mechanical and civil constructions' technical life. This type of cost has been compared for quite a number of SWRO desalination plants realized, under construction or being planned. The following general split can be made for the TCO [29]:

- ±17% Pretreatment
- ± 6% RO membrane replacement and RO
- membrane cleaning
- ±27% Other fixed costs (amortization of other
- equipment etc.).
- ±50% Other variable costs (energy costs etc.).

3.2. Effects of Membrane Structure and Technology, and Brine Management on the Costs and Energy Concerns of the RO Process

RO membranes are a fundamental and important part of the desalination process [30]. In the last two decades or so, membrane technology has gained a massive importance and is now competing with other separation methods and technologies in terms of energy efficiency, selective separation, high separation capacity, and capital investments. Several industries have adopted and converted to a membrane separation process in place of the conventional separation processes, so in water desalination conventional thermal technologies are being increasingly replaced with RO technologies [31].

Permeability of RO membranes and their salt rejection capacity have undergone significant improvements in recent years. Energy consumption in RO systems has significantly reduced from around 26 kWh/m^3 in 1980 to around 3.4 kWh/m^3 in recent years owing to these and other improvements. Nevertheless, there are further opportunities for improving the permeability of RO membranes using different membrane materials so as to minimize energy consumption, with a general goal of at least doubling the current generation's permeability. The new generation of RO membranes include nanocomposites, nanotubes and biomimetic membranes. Their working principles, effects on energy, advantages and disadvantages are summarised in Table 2 [4].

Table 2 Comparison of new generation RO membranes [4]

Membrane type	Principle	Energy consumption	Advantages	Disadvantages
Nanocomposite	Zeolite nanoparticles incorporated in a polyamide matrix creating enhanced transport of water molecules.	20 % lower energy consumption than conventional seawater RO membranes.	More than double the flux of currently available seawater RO membranes.	Chemical compatibility and structural stability is not known. Rejection of specific contaminants is not known. Long-term operational data

				not available.
Nanotubes	Transport of water molecules through structured carbon and boron nitride nanotubes.	30 % to 50% lower energy consumption than conventional seawater RO membranes.	Ten-fold higher flux than currently available seawater RO membranes.	Only modeling results available. Rejection of specific contaminants is not known.
Biomimetic	Aquaporins used to regulate transport of water molecules.	Energy consumption is not known.	Hundred times more permeable than currently available seawater RO membrane.	Inability to withstand high operating pressures. Rejection of specific contaminants is not known. Long-term operational data not available.

Calculations of the effect of membrane cost on water production cost can be done by considering the amortized membrane cost per unit permeate produced (also known as the specific membrane cost, [SMC]). SMC for a single-stage RO process at the limit of thermodynamic restriction is given by Eq. (18):

$$SMC_{tr,norm} = \frac{m}{L_p R(\pi_0)^2 \left[\frac{1}{1-Y} - \frac{1}{Y}\ln\left(\frac{1}{1-Y}\right)\right]} \quad (18)$$

Where: L_p – Membrane hydraulic permeability (m/Pa·s),

m – Amortized membrane price in equivalent energy units per unit area ($m = \beta m_A/\varepsilon$ where m_A is amortized membrane unit price, (\$/m^2·s).

For the same product's water recovery, the normalized specific membrane cost ($SMC_{tr,norm}$) decreases with increasing membrane hydraulic permeability, salt rejection and feed osmotic pressure [32].

Brine, which is the by-product of RO desalination, requires proper management and subsequent disposal which is environmentally friendly. This has an effect on the costs incurred. Specific brine management cost (SBC) cost per unit volume of produced permeate is calculated using Eq. (19):

$$SBC_{norm} = \frac{SBC}{\pi_0} = \frac{b(1-Y)}{\pi_0 Y} \quad (19)$$

Where: b – concentrate (brine) management cost (\$/m^3 brine volume) which can be expressed by equivalent energy units.

For a single-stage RO process without energy recovery but with an ideal pump ($\eta_{pump} = 1$, $\eta_{ERD} = 0$), the cost of brine management and energy consumption combined is given by Eq. (20):

$$SEC_{tr,norm}^{ERD} + SBC_{norm} = \frac{1}{Y(1-Y)} + \frac{b(1-Y)}{\pi_0 Y} \quad (20)$$

To minimize the RO process cost, Eq. (21) calculates the optimal water recovery as follows:

$$Y_{opt} = \frac{\sqrt{1+b_{norm}}}{1+\sqrt{1+b_{norm}}} \quad (21)$$

Where $b_{norm} = b/\pi_0$. Brine management cost shifts the optimal water recovery to a higher value [32].

Membrane configuration of the unit has a major effect on performance and economics of the RO plant. Two-stage and six-element-per-vessel units were the usual configuration in the past, whereas the current units consist of a single stage with seven elements per vessel. There is a cost advantage in the increased number of elements per vessel [10]. A useful approach to improving the process design of membrane desalination is to emulate developed optimization strategies from other separations processes like distillation that recycle one or both counter-current flowing streams through the use of multistage processing [20].

The crucial shortcoming of the RO membranes is susceptibility to fouling. Membrane fouling leads to higher operational costs which include higher energy demand, increase in frequency of cleaning and maintenance, and reduced lifetime of the membrane elements [30].

3.2. Pre-Treatment of Saline Water and its Effects

Naturally, water contains very small suspended particles (approximately 0.1 micron, defined as colloidal). The surface to mass ratio is huge compared to visible particles which cause them to deposit in unlimited patterns and therefore add up and thicken where they deposit. This accumulation and deposition of particles on membrane surfaces results in what are known as amorphous gels. Such membrane fouling agents are complex mixtures and are difficult, sometimes impossible, to clean [33]. Through pre-treatment, fouling is significantly reduced, if not prevented. There is also a possible reduction in the damage to reverse osmosis membranes. The pre-treatment method to be used depends on the extremes of the characteristics of the raw water [34]. Effective pre-treatment of saline water is required in order to increase efficiency and to increase membrane life time. Appropriate pre-treatment will maximize the process efficiency and increase membrane life by reducing formation of scales, fouling deposition and degradation of the membrane. The benefits of the pre-treatment will be product flow optimization, salt rejection optimization and product recovery, reduction of operating costs, and reduction or decrease in cleaning frequency and membrane replacement costs. There are several types of pre-treatment methods. These include coagulation, filtration, scale control and chlorination-dechlorination [17, 34]. Economic comparisons of the costs of pre-treatment methods, for example membrane filtration versus granular filtration, are intricate since they involve assumptions on the anticipated long-term performance. The experience of the evaluator heavily influences such assumptions [35].

The cost of operation of RO technology can be increased due to the frequency of membrane replacement. However, pre-treatment by means of low-pressure membrane filtration has proven to increase the membrane lifespan by 20 % to 30 % thereby improving the cost of RO in the long-term [33]. The cost of pre-treatment can be split into operating costs and amortization of investment (mainly chemicals for disinfection and coagulation). When an ulta-filtration (UF) is selected as a pre-treatment method over a conventional one, there is an increase in investment costs for pre-treatment. Consequently, there is also an increase in the fixed costs associated with pre-treatment. The chemicals costs (mainly coagulant) will decrease, but the cost of UF membrane replacement is introduced. When conventional pre-treatment is used, the TCO of the SWRO desalination plant is approximately 85 US cents/m^3 to 90 US cents/m^3 whereas when UF is used, the TCO of the dual membrane desalination plant reduces to between 79 US cents/m^3 and 88 US cents/m^3. This shows that there is a reduction of 2 % to 7 % in TCO when UF is used compared with conventional pre-treatment methods [29]. Energy and cost comparisons of conventional and micro-filtration/ ultra-filtration, MF/UF pre-treatment methods are summarised in Table 3.

Table 3 Summarised comparison of MF/UF and conventional pre-treatment methods [34]

	Conventional pre-treatment	MF/UF pre-treatment	Benefits
Capital costs	Cost competitive with MF/UF	Slightly higher than conventional pre-treatment. Costs continue to decline as developments are made	Capital costs of MF/UF could be 0–25% higher, whereas life cycle costs using either of the treatment schemes are comparable
Footprint	Calls for larger footprint	Significantly smaller footprint	Foot print of MF/UF could be 30-50 % of conventional filters.
Energy requirements	Less than MF/UF as it could be gravity flow	Higher than conventional	MF/UF requires pumping of water through the membranes. This can vary depending on the type of membrane and water quality
Chemical costs	High due to coagulant and process chemicals needed for optimization	Chemical use is low, dependent on raw water quality	Less chemicals
RO capital cost	Higher than MF/UF since RO operates at lower flux	Higher flux is logically possible resulting in lower capital cost	Due to lower SDI values, RO can be operated at 20% higher flux if feasible, reducing RO capital costs
RO operating costs	Higher costs as fouling potential of RO feed water is high resulting in higher operating pressure. Frequent cleaning of RO membranes.	Lower RO operating costs are expected due to less fouling potential and longer membrane life.	The NDP (net driving pressure) is likely to be lower if the feed water is pre-treated by MF/UF. Membrane cleaning frequency is reduced by 10 %, reducing system downtime and prolonged element life.

Figure 5 shows the step by step procedure undertaken to produce pre-treated saline water to be fed into a desalination plant.

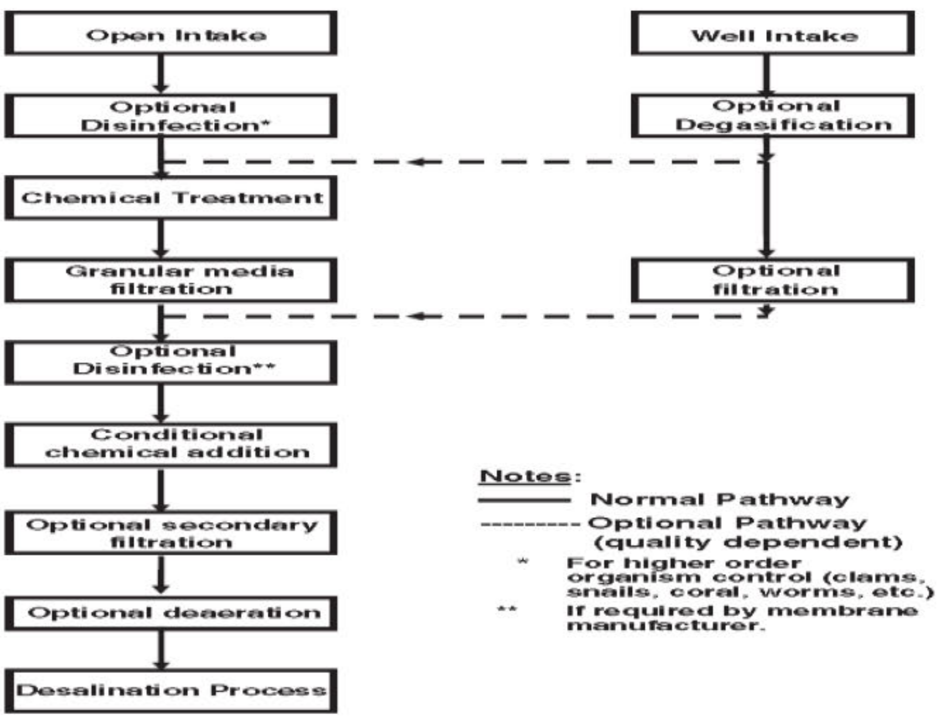

Figure 5 Pre-treatment technique [35].

Pre-treatment benefits include the optimization of:

- Salt rejection,
- Product flow,
- Product recovery,
- Greater plant availability resulting from consistent production of excellent RO feed water and reduced cleaning requirements,
- Extended life of the RO membranes,
- Reduced operating and membrane replacement cost [17, 36].

There are several effects and possible consequences of poor pre-treatment of the RO plant. Initial signs are an increase in feed pressure required by the system, which is generally complemented by frequent requirement of RO chemical cleaning. This net driving pressure increase can normally be credited to one or more of the foulant types. The effects and consequences of poor pre-treatment include:

- Increased RO feed pressure resulting in higher power consumption,
- Lower plant availability and increased chemical costs owing to increase in cleaning frequency,
- Reduced membrane lifespan due to frequent cleaning, thereby increasing the rate of membrane replacement and subsequent costs,
- Mechanical damage of membrane elements due to excessive pressure drop especially if water hammer occurs during transient phases of operation,
- Membrane damage is increased caused by overuse of cleaning agents or biocides,
- Degradation of RO permeate quality due to concentration polarization or damaged membranes,
- Higher backwash frequency in the filtration units,
- Cartridge filter consumption is increased, and
- Chemical consumption of the pre-treatment system is increased.

If the root causes of the poor pre-treatment cannot be identified and addressed on time, the costs of desalination will increase and, in some cases, productivity decline. Permanent reduction in design capacity or subsequent shut-down may occur unless and until there is pre-treatment system re-designing [37].

4. CONCLUSION

Several studies have shown that the effects of energy consumption in RO desalination has been a thorn in researchers' flesh. Energy consumption has a negative impact on costs of running the plants and subsequently affects the costs of potable water production. Studies on reduction of energy consumption in desalination have been one of the major priorities in recent years and the results have been very significant. The incorporation of energy recovery devices has led to major benefits in the technology as some of the energy is recycled and turned into productive use. Research and development of energy and cost-effective desalination technologies has been, and still is, an ongoing process as sources of fresh water continue to diminish at an alarming rate whereas population growth is increasing dramatically.

REFERENCES

[1] Kalogirou, S.A. Seawater Desalination Using Renewable Energy Sources. *Progress in Energy and Combustion Science*, 31, 2005, pp. 242-281. https://doi.org/10.1016/j.pecs.2005.03.001

[2] Lee, K.P., Arnot, T.C., and Mattia, D. A Review of Reverse Osmosis Membrane Materials for Desalination—Development to Date and Future Potential. *Journal of Membrane Science*, 370, 2011, pp. 1-22. https://doi.org/10.1016/j.memsci.2010.12.036

[3] Shahabi, M., McHugh, A., Anda, M., and Ho, G. A Framework for Planning Sustainable Seawater Desalination Water Supply. *Science of the Total Environment*, 575, 2016, pp. 826-835. https://doi.org/10.1016/j.scitotenv.2016.09.136

[4] Subramani, A., Badruzzaman, M., Oppenheimer, J., and Jacangelo, J.G. Energy Minimization Strategies and Renewable Energy Utilization for Desalination: A Review. *Water Research*, 45, 2011, pp. 1907-1920. https://doi.org/10.1016/j.watres.2010.12.032

[5] Mathioulakis, E., Belessiotis, V., and Delyannis, E. Desalination by Using Alternative Energy: Review and State-of-the-Art. *Desalination*, 1, 2007, pp. 346-365. https://doi.org/10.1016/j.desal.2006.03.531

[6] Sadhwani, J. and Veza, J. Desalination and Energy Consumption in Canary Islands. *Desalination*, 221, 2008, pp. 143-150. https://doi.org/10.1016/j.desal.2007.02.051

[7] Miller, S., Shemer, H., and Semiat, R. Energy and Environmental Issues in Desalination. *Desalination*, 366, 2015, pp. 2-8. https://doi.org/10.1016/j.desal.2014.11.034

[8] Al-Karaghouli, A. and Kazmerski, L.L. Energy Consumption and Water Production Cost of Conventional and Renewable-Energy-Powered Desalination Processes. *Renewable and Sustainable Energy Reviews*, 2013, pp. 343-356. https://doi.org/10.1016/j.rser.2012.12.064

[9] Lapuente, E. Full Cost in Desalination. A Case Study of the Segura River Basin. *Desalination*, 300, 2012, pp. 40-45. https://doi.org/10.1016/j.desal.2012.06.002

[10] Wilf, M. and Bartels, C. Optimization of Seawater RO Systems Design. *Desalination*, 173, 2005, pp. 1-12. https://doi.org/10.1016/j.desal.2004.06.206

[11] Veerapaneni, S., Long, B., Freeman, S., and Bond, R. Reducing Energy Consumption for Seawater Desalination. *Journal-American Water Works Association*, 99, 2007, pp. 95-106. https://doi.org/10.1002/j.1551-8833.2007.tb07958.x

[12] Gude, V.G. Energy Consumption and Recovery in Reverse Osmosis. *Desalination and water treatment*, 36, 2011, pp. 239-260. https://doi.org/10.5004/dwt.2011.2534

[13] Zhu, A., Christofides, P.D., and Cohen, Y. Energy Consumption Optimization of Reverse Osmosis Membrane Water Desalination Subject to Feed Salinity Fluctuation. *Industrial & Engineering Chemistry Research*, 48, 2009, pp. 9581-9589. https://doi.org/10.1021/ie900729x

[14] Gao, L., Rahardianto, A., Gu, H., Christofides, P.D., and Cohen, Y. Energy-Optimal Control of RO Desalination. *Industrial & Engineering Chemistry Research*, 53, 2013, pp. 7409-7420. https://doi.org/10.1021/ie402304d

[15] Zhu, A., Christofides, P.D., and Cohen, Y. Effect of Thermodynamic Restriction on Energy Cost Optimization of RO Membrane Water Desalination. *Industrial & Engineering Chemistry Research*, 48, 2008, pp. 6010-6021. https://doi.org/10.1021/ie800735q

[16] Elimelech, M. and Phillip, W.A. The Future of Seawater Desalination: Energy, Technology, and the Environment. *Science*, 333, 2011, pp. 712-717. 10.1126/science.1200488

[17] Avlonitis, S., Kouroumbas, K., and Vlachakis, N. Energy Consumption and Membrane Replacement Cost for Seawater Ro Desalination Plants. *Desalination*, 1, 2003, pp. 151-158. https://doi.org/10.1016/S0011-9164(03)00395-3

[18] Al-Karaghouli, A. and Kazmerski, L. Economic and Technical Analysis of a Reverse-Osmosis Water Desalination Plant Using Deep-3. 2 Software. *Journal of Environmental Science and Engineering A*, 1, 2012, pp. 318-328.

[19] Semiat, R. Energy Issues in Desalination Processes. *Environmental science & technology*, 42, 2008, pp. 8193-8201. https://doi.org/10.1021/es801330u

[20] Chong, T.H., Loo, S.-L., and Krantz, W.B. Energy-Efficient Reverse Osmosis Desalination Process. *Journal of Membrane Science*, 473, 2015, pp. 177-188. https://doi.org/10.1016/j.memsci.2014.09.005

[21] Feinberg, B.J., Ramon, G.Z., and Hoek, E.M. Thermodynamic Analysis of Osmotic Energy Recovery at a Reverse Osmosis Desalination Plant. *Environmental Science & Technology*, 47, 2013, pp. 2982-2989. https://doi.org/10.1021/es304224b

[22] Malek, A., Hawlader, M., and Ho, J. Design and Economics of RO Seawater Desalination. *Desalination*, 105, 1996, pp. 245-261. https://doi.org/10.1016/0011-9164(96)00081-1

[23] Ziolkowska, J.R. Is Desalination Affordable?—Regional Cost and Price Analysis. *Water Resources Management*, 5, 2015, pp. 1385-1397. 10.1007/s11269-014-0901-y

[24] Hossam-Eldin, A., El-Nashar, A., and Ismaiel, A. Techno-Economic Optimization of SWRO Desalination Using Advanced Control Approaches. *Desalination and Water Treatment*, 12, 2009, pp. 389-399. https://doi.org/10.5004/dwt.2009.965

[25] Papapetroua, M., Cipollinaa, A., La Commarea, U., Micalea, G., Zaragozac, G., and Kosmadakisb, G. Assessment of Methodologies and Data Used to Calculate Desalination Costs. *Desalination*, 419, 2017, pp. 8-19. https://doi.org/10.1016/j.desal.2017.05.038

[26] Childs, W.D. and Dabiri, A.E. Desalination Cost Savings of VARI-RO™ Pumping Technology. *Desalination*, 87, 1992, pp. 109-135 https://doi.org/10.1016/0011-9164(92)80137-X

[27] Poullikkas, A. Optimization Algorithm for Reverse Osmosis Desalination Economics. *Desalination*, 133, 2001, pp. 75-81. https://doi.org/10.1016/S0011-9164(01)00084-4

[28] Wittholz, M.K., O'Neill, B.K., Colby, C.B., and Lewis, D. Estimating the Cost of Desalination Plants Using a Cost Database. *Desalination*, 229, 2008, pp. 10-20. https://doi.org/10.1016/j.desal.2007.07.023

[29] Knops, F., van Hoof, S., Futselaar, H., and Broens, L. Economic Evaluation of a New Ultrafiltration Membrane for Pretreatment of Seawater Reverse Osmosis. *Desalination*, 203, 2007, pp. 300-306 https://doi.org/10.1016/j.desal.2006.04.013

[30] Prihasto, N., Liu, Q.-F., and Kim, S.-H. Pre-Treatment Strategies for Seawater Desalination by Reverse Osmosis System. *Desalination*, 1, 2009, pp. 308-316. https://doi.org/10.1016/j.desal.2008.09.010

[31] Drioli, E., Stankiewicz, A.I., and Macedonio, F. Membrane Engineering in Process Intensification—an Overview. *Journal of Membrane Science*, 380, 2011, pp. 1-8. https://doi.org/10.1016/j.memsci.2011.06.043

[32] Zhu, A., Rahardianto, A., Christofides, P.D., and Cohen, Y. Reverse Osmosis Desalination with High Permeability Membranes—Cost Optimization and Research Needs. *Desalination and Water Treatment*, 15, 2010, pp. 256-266. https://doi.org/10.5004/dwt.2010.1763

[33] Jamaly, S., Darwish, N., Ahmed, I., and Hasan, S. A Short Review on Reverse Osmosis Pretreatment Technologies. *Desalination*, 354, 2014, pp. 30-38. https://doi.org/10.1016/j.desal.2014.09.017

[34] Vedavyasan, C., Pretreatment Trends—an Overview. *Desalination*, 203, 2007, pp. 296-299. https://doi.org/10.1016/j.desal.2006.04.012

[35] 35. Sutzkover-Gutman, I. and Hasson, D. Feed Water Pretreatment for Desalination Plants. *Desalination*, 264, 2010, pp. 289-296. https://doi.org/10.1016/j.desal.2010.07.014

[36] Wolf, P.H., Siverns, S., and Monti, S. Uf Membranes for RO Desalination Pretreatment. *Desalination*, 182, 2005, pp. 293-300. https://doi.org/10.1016/j.desal.2005.05.006

[37] Henthorne, L. and Boysen, B. State-of-the-Art of Reverse Osmosis Desalination Pretreatment. *Desalination*, 356, 2015, pp. 129-139. https://doi.org/10.1016/j.desal.2014.10.039

CHAPTER 4. Modeling and Optimization of Reverse Osmosis Desalination Plants

This chapter is a critical review on the mathematical modeling and optimization of RO desalination plants. Several modeling techniques of mass and heat transfer, salt rejection and membrane solute permeability, including genetic algorithms (GA) and neural networks techniques were reviewed and also improvement of dynamic response to eliminate steady state errors. Control system of the plant using PID controllers was also analysed. This article was published in the International Journal of Mechanical Engineering and Technology (IJMET).

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MODELLING AND OPTIMIZATION OF REVERSE OSMOSIS DESALINATION PLANTS

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ABSTRACT

Research on the modelling and optimization of reverse osmosis (RO) desalination plants is ongoing in order to come up with sustainable and efficient RO plants. Several techniques have been employed to come up with mathematical models of mass and heat transfer, salt rejection and membrane solute permeability, including genetic algorithms (GA) and neural networks techniques. Incorporation of PID controllers have been well known and widely used to improve the dynamic response as well as to reduce or eliminate the steady state errors and improve responses.

Keywords: Desalination, Reverse Osmosis, Neural Networks, Genetic Algorithm, Optimization.

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1. INTRODUCTION

Clean water is one of the fundamental needs for every individual in the world and is embedded in SDG 6 of the 2030 Agenda for Sustainable Development, which seeks to promote the availability and sustainable management of water and sanitation for all. Population increase, climate change and geographical accessibility are some of the major reasons why water has become a very scarce commodity. To provide sufficient fresh water, alternative water resources, such as seawater and wastewater, have been investigated [1]. Reverse osmosis (RO), has played a very important role in trying to alleviate this problem. Several studies have been made on the modelling and optimization of RO plants.

The study, control, optimal operation and design of RO plants need adequate models. These models can vary in size and complexity according to the intended application [2]. Instrumentation and control is required in the RO system to control and monitor every process such as feed flow and the quality of water produced (pH, conductivity, turbidity), flow rates and pressure, feed pressure controls, and tank levels management [3].

2. MATHEMATICAL MODELING OF A REVERSE OSMOSIS SYSTEM

There are two basic approaches in the mathematical modeling of any process. The first approach is the knowledge based approach which uses theoretical or parametric models based on fundamental and essential knowledge (mechanisms) of the process, and the second approach is the empirical or the non-parametric models, which do not involve the knowledge of the fundamental principles governing the process [4]. There are many approaches that have been used to model RO systems, including models of membranes [5, 6], modelling of RO plants using neural networks [7] and various algorithms [8, 9].

2.1. Neural Networks

Neural networks (NN) are mathematical models that are designed and intended to imitate certain features of neurological functioning of the brain. Neural networks are parallel structures that consist of non-linear processing elements known as nodes or neurons, interrelated by fixed or variable weights (Figure 1). The neurons are assembled into layers and typical networks usually comprise an input layer, an output layer and at least one hidden layer [7]. These signals (layers) are weighted and summed up. The results (potentials of the neurons) are computed by a transfer function which transmits the output to the other nodes, then to the outside environment of the network. NNs comprise a very large number of basic computational elements which are organised in a massive parallel set. These networks are then developed in artificial synapses that interconnect these elements that are categorized by a set of weights, which can usually be adjusted by a learning process. Programming is not necessary in this model, instead, examples are used to learn how to deal with more intricate and complex relationships [10]. One of the most widely used mathematical models in membrane processing application is known as the artificial neural network (ANN) model. ANN is a non-linear processing system operating in parallel, comprising connections and nodes. Connections consist of weight with nodes addressing information. A node consists of a neuron which is a single computational processor [11].

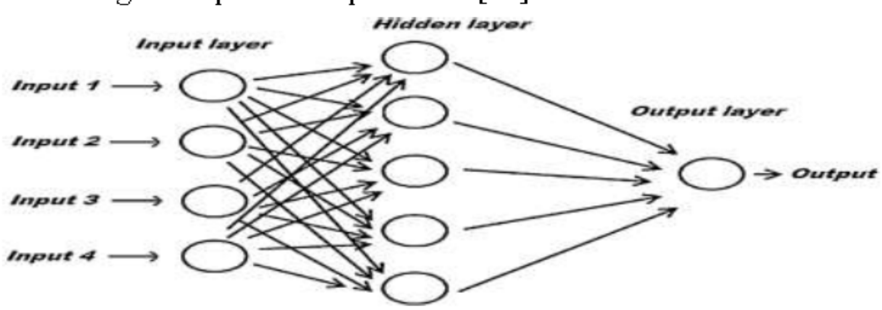

Figure 1. Feedforward neural network with one hidden layer[12].

Present studies most commonly use sigmoid or squashing transfer functions, and the general form is given by Eq. (1):

$$f(x) = \frac{1}{1 + e^{-x}} \quad (1)$$

This squashing function transforms input to output bounded in the 0 to 1 range. An optimization procedure is used to determine the weights in neural networks by using the difference between desired output and the calculated output [11].

In the ANN model, appropriate selection parameters such as the number of hidden neurons in each layer, number of hidden layers, momentum coefficient, learning rate, number of iterations and training function improve the prediction performance. The use of fewer hidden layers and neurons reduces the intricacy of the ANN model by decreasing the training time and the risks of over-fitting, the possibility of having numerous minimum solution and calculation errors of the network weights, and also makes extract of information from ANN easier [13]. Too large values increases the speed of the convergence but the network becomes unstable and may converge to local minima instead of a global minima. A momentum coefficient is introduced in a neural network to decrease the convergence time; a high momentum value leads to oscillation whereas a lower value leads to slow convergence. The number of neurons in the hidden layer is obtained using Eqs. (2) and (3):

$$nm = \sqrt{n+m} + a \tag{2}$$

$$\frac{N}{TW} \geq 1 \tag{3}$$

where n is number of input variable, m is number of output variable and the parameter, a is varying from 1 to 10, N is total number of data points, and TW is total number of weights [11].

2.2. Genetic Algorithm

Charles Darwin's theory of evolution inspired the genetic algorithm (GA) method of selection where the survival of the fittest creature and their genes are simulated so as to come up with the highest performing genes. It is a population-based algorithm. Parameters are represented by genes and solutions correspond to chromosomes. Evaluation of each individual's fitness in the population is performed using a fitness function. In order to improve poor solutions, random selection of best solutions is performed using different mechanisms e.g. a roulette wheel. In this mechanism, best solutions are produced since the probability is proportional to the fitness (objective value). Choosing of poor solutions is reduced as well, meaning that if good solutions are selected, they can be pulled out with other solutions [14]. The value of the objective function of each chromosome is taken as the fitness of the chromosome and another parameter called fitness function is defined in Eq. (4):

$$Fitness\ Function = \frac{f(s_i(t))}{\sum_{j=1}^{M} f(s_i(t))} \tag{4}$$

where $f(s_i(t))$ is fitness of the chromosome s_i and the denominator represents the sum of the fitness of all the members of the population [15].

Holland first proposed the basic principles of GA. GA uses a direct resemblance of such natural evolution to perform global optimization so as to solve highly complex and intricate problems [16]. GA methodology involves four basic steps which are initialization, selection, reproduction and termination [17]. The selection mechanism determines which individuals are chosen for mating (reproduction) and how many offspring each selected individual produces. The main principle of selection strategy is "the chance of being a parent increases for a better individual." Generally, crossover and mutation explore the search space, whereas selection reduces the search area within the population by discarding poor solutions. However, worst individuals should not be discarded and they have some chances to be selected because it may lead to useful genetic material. A good search technique must find a good trade-off between exploration and exploitation in order to find a global optimum [18].

It presumes that the potential solution of a problem is an individual and can be represented by a set of parameters. These parameters are regarded as the genes of a chromosome and can be structured by a string of concatenated values. The form of variables representation is defined by the encoding scheme. The variables can be represented by binary, real numbers, or other forms, depending on the application data. Its range, the search space, is usually defined by the problem [18].

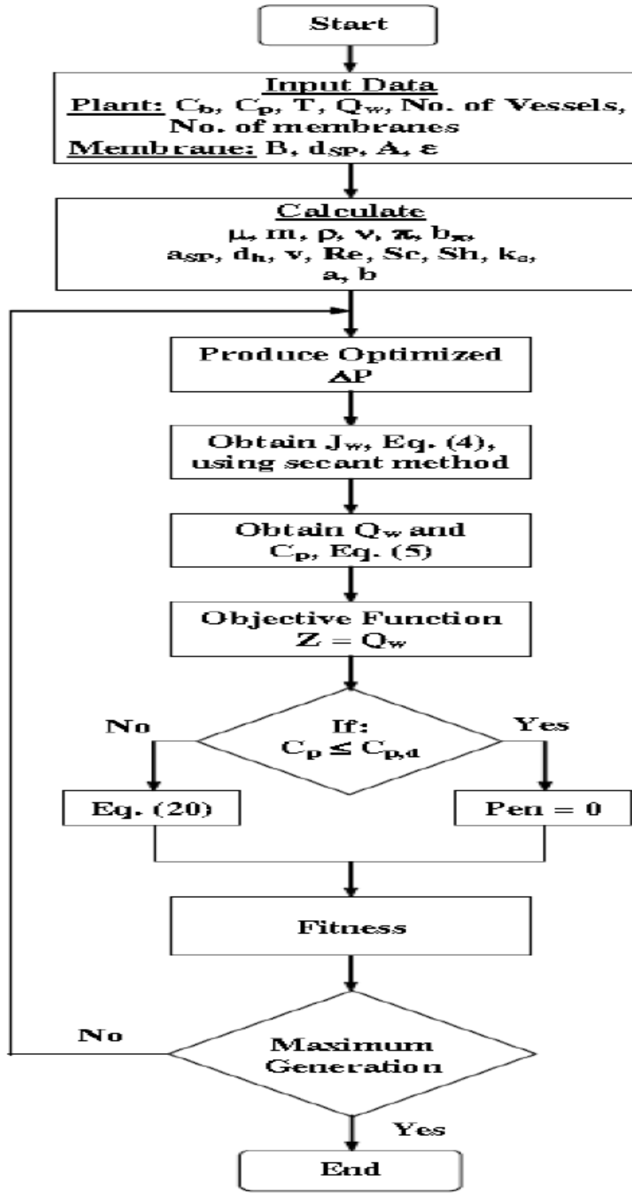

Figure 2. Flow chart for optimization of RO using genetic algorithm[19].

To model and obtain the relationship between the variables, common transport models describing RO phenomenon were studied. The Spiegler-Kedem model was found to give satisfactory results. Moreover, the Spiegler-Kedam model was shown to accurately represent the RO system under investigation (14–19). Thus, for the present study, the above model was chosen. The Spiegler-Kedem model is based on irreversible thermodynamics and involves three parameters. Eq. (5) mathematically expresses the model as shown:

$$\frac{R_o}{1-R_o} = \left[\frac{\sigma}{1-\sigma}\right]\left[1-e^{-\frac{J_v(1-\sigma)}{P_M}}\right]e^{-\frac{J_v}{k}} \quad (5)$$

where R_o is the observed rejection of solute; $\sigma$is the reflection coefficient with 0 for no rejection and 1 for total rejection; J_v is the volumetric flux across the membrane; P_M is the local solute permeability per unit membrane thickness, and; k is the mass transfer coefficient.

The following equations were employed to optimize the performance of the RO desalination system using the GA technique and produce the best operating pressure difference across membrane ΔP which maximizes permeate volumetric flow rate Q_w and fulfils the permeate concentration constraint $C_{p,di}$ [19].

For a given RO system layout (number of channels, membrane area, etc.), the single objective function Z to be maximized is:

$$Z = Q_w \quad (6)$$

Optimization of an existing RO system is a constrained optimization problem. The constraint applied in such system is given as:

$$C_p \le C_{p,di} \quad (7)$$

The bounds on ΔP are specified as follows:

$$\Delta P_{min} \le \Delta P \le \Delta P_{max} \quad (8)$$

where ΔP_{min} and ΔP_{max} are the minimum and maximum allowable pressure differences across the membrane.

In optimization techniques, external penalty functions are used to convert a constrained problem into an unconstrained problem. Therefore, for the RO system optimization, the objective function Z is given as:

$$Z = Q_w - Pen \quad (9)$$

where, Pen is the penalty subtracted from the objective function.

The penalty function is written as:

$$Pen = C_{Pen}\left(\frac{C_p}{C_{p,d}} - 1\right) \quad (10)$$

where, C_{pen} is the penalty function constant and is chosen as big as 100 000. Therefore, the objective function can be calculated from:

$$Z = \begin{cases} Q_w & if\ C_p \le C_{p,d} \\ Q_w - C_{pen}\left(\frac{C_p}{C_{p,d}} - 1\right) & otherwise \end{cases} \quad (11)$$

The penalty function is applied when the permeate concentration is not less than the desired permeate concentration.

GAs have several advantages that include adaptability, robustness and flexibility [20]. Other advantages of GAs over the traditional derivative based optimisation algorithms are that they provide global optimum solutions that ensure convergence. Owing to these advantages, GAs can be employed in nearly all types of problems and also do not need complete mathematical knowledge of the problem [21].

3. CONTROL SYSTEMS

The RO process control loops are as simple as the process itself. The main objective of RO is to maintain a constant rate of water production with tolerable and acceptable purity. Researchers in the 1980s suggested an incremental on/off control system that is simple enough to suit the nature of the RO rate. A system of this nature requires a large buffer system to meet the demand surges and the system design must be based on the average demand value to minimise on/off frequency of the membrane modules [22].

3.1. PID Controllers

The PID (proportional integral derivative) controller is well known and widely used to improve the dynamic response as well as to reduce or eliminate the steady state error. The derivative controller adds a finite zero to the open loop plant transfer function and improves the transient response. The integral controller adds a pole at the origin, thus increasing system type by one and reducing the steady state error due to a step function to zero. PID control consists of three types of control: proportional, integral, and derivative control [16].

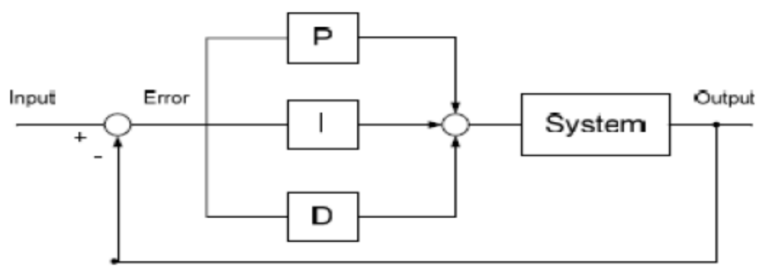

Figure 3. Conventional PID controller schematics [16].

The objective of a controller is to achieve the relationship shown in Eq. (12):

$$\lim_{t\to\infty} e(t) = 0 \qquad (12)$$

Eq. (13) then shows an expression that is used to define the PID controller:

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{d}{dt}\big(e(t)\big) \qquad (13)$$

In the frequency domain, the modified version of PID controller is given by:

$$u(s) = K_P e(s) + \frac{K_I e(s)}{s} + \frac{K_D N e(s) s}{s+N} \qquad (14)$$

where K_P, K_I, and K_D are nonnegative constants, s is the complex variable of the Laplace transform and Nis a constant (N >> 1). These parameters are tuned to achieve stability with the required performance [23]. Kim *et al.* in 2008 [16] proposed an advanced auto-tuning RO PID controller to search for optimal gain parameters using a GA method. Figure 4 shows the schematics. Optimal parameters of PID controllers are usually difficult to determine and for this reason, several artificial intelligence (AI) methods have been used to determine and come up with the optimal parameters, therefore improving the performance of controllers. These AI methods include, but are not limited to: differential evolution (DE) algorithm, evolutionary algorithm, multi-objective optimization, fuzzy systems, simulated annealing (SA), genetic algorithm (GA), artificial bee colony (ABC), many optimizing liaisons (MOL), tabu search (TS) algorithm, and particle swarm optimization (PSO) [24]. Figure 4 shows a schematic diagram where GA is applied to the tuning of PID controller gains to ensure optimal control performance at nominal operating [25].

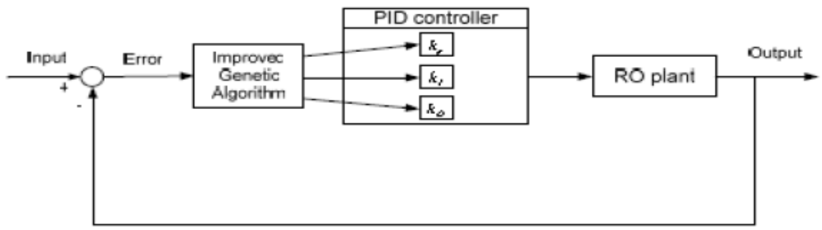

Figure 4. Auto tuning PID controller schematics based on improved GA for RO plants[16].

4. OPTIMIZATION OF THE SYSTEM

The performance of a membrane process is limited by the magnitude of the chemical potential driving force for mass transfer. This driving force can be maximised by manipulating the temperature or pressure of the feed stream which requires significant energy. This spending should be balanced against other costs in designing the membrane system. Consequently, proper optimization techniques are required to determine the best values for the various operating and design parameters. Eq (15) to Eq (30) are used in the determination of the optimization strategy which considers both operating and design parameters. The results of these non-linear optimization problems are solved using the gPROMS software by the application of sequential quadratic programming (SQP) method. The effect of different operating and design parameters on membrane performance was studied by varying one parameter and keeping the others constant as seen in the following equations [26]:

a. Water flux, J_w:

$$J_w = A(\Delta P - \Delta\pi) \quad (15)$$

b. Solute flux, J_s:

$$J_s = B(C_m - C_p) \quad (16)$$

c. Recovery, R %:

$$R = \frac{Q_p}{Q_m} * 100\% \quad (17)$$

d. Concentration polarization, CF:

$$CF = \frac{C_m - C_p}{C_b - C_p} = e^{\frac{J_v}{K}} \quad (18)$$

e. Salt rejection, SR %:

$$SR = \left(1 - \frac{C_p}{C_f}\right) * 100 \quad (19)$$

f. Pressure drop, ΔP_f:

$$\Delta P_f = \frac{\rho u^2 L C_{td}}{2d_h} \quad (20)$$

g. Mass transfer coefficient, Sh:

$$Sh = \frac{K d_h}{D} = 0.064 K_{dc} Re^{0.75} Sc^{0.33} \left(\frac{2d_h}{L_f}\right)^{0.5} \quad (21)$$

h. Mass balance, $Q_f C_f$:

$$Q_f C_f = Q_p C_p + Q_r C_r \quad (22)$$

i. Flow balance, Q_f:

$$Q_f = Q_p + Q_r \quad (23)$$

j. Average bulk concentration, Q_B:

$$Q_B = \frac{Q_f + Q_r}{2} \quad (24)$$

k. Average velocity in feed, U:

$$U = \frac{Q_B}{W h_{sp} \varepsilon} \quad (25)$$

l. Water flow via membrane, Q_p:

$$Q_p = J_w S \quad (26)$$

m. Material balance around membrane, C_p:

$$C_p = \frac{J_s}{J_w} \quad (27)$$

n. Specific energy, E:

$$E = \frac{\Delta P_f Q_f}{\eta Q_p} \quad (28)$$

o. With turbine energy recover (ER), E:

$$E = \frac{\frac{\Delta P_f Q_f}{\eta} - P_r Q_r \eta_T}{Q_p} \quad (29)$$

p. With pressure exchange (PX) energy recovery ER, E:

$$E = \frac{\Delta P_f Q_p}{\eta Q_p} \quad (30)$$

Osmotic pressure of the feed water is an important factor in most reverse osmosis processes. Osmotic pressure resulting from the dispersal force of salts in a solution is usually a monotonic function of salt concentration. It has been noted from practical observations that a linear relationship often exists between osmotic pressure and salt concentration. For a nonionizing solute, the osmotic pressure $\Delta\pi$ can be determined with the Van't Hoff formula as shown in Eq. (31):

$$\Delta\pi = \frac{RT(C_f - C_p)}{M_w} \quad (31)$$

where R is the universal gas constant; T is the absolute temperature; $C_f - C_p$ is the salt concentration difference between the feed and the permeate; and M_w is the molar molecular weight of the solute[27].

Empirical relationships are usually employed to determine the osmotic pressure based on a collective measurement of the total amount of salts in water, usually the total dissolved solids (TDS). Eq. 32 shows the empirical equation of osmotic pressure as shown:

$$\Delta\pi = f_{os}(C_f - C_p) \quad (32)$$

where f_{os} is the osmotic coefficient that converts salt concentration, TDS, in term of mg/LTDS to osmotic pressure [27].

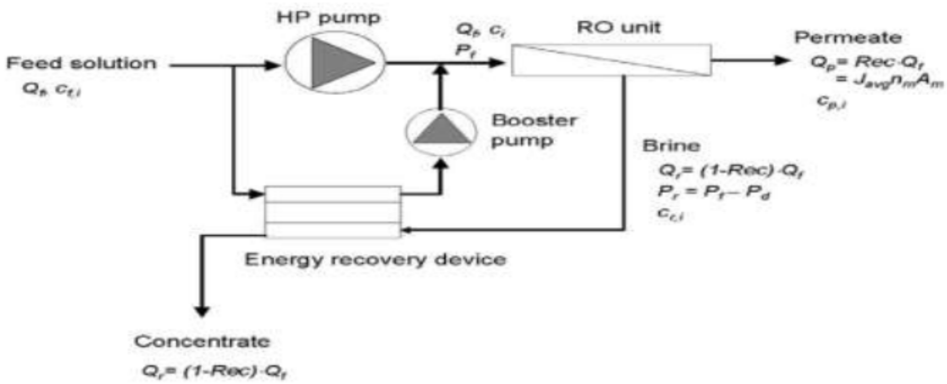

Figure 5. A schematic diagram of RO desalination process [28].

Figure 5 shows the schematic diagram of a RO desalination process and is used to calculate all the above parameters for the optimization of the system.

5. CONCLUSION

Mathematical modelling and optimization of the RO system can be done using several techniques including ANN and GA incorporating PID controllers. Researchers and scholars have studied these techniques in the RO desalination. GA has given the best outcomes as it is used to select the best attributes from a sample of different attributes from several plants. Neural networks have the attributes of providing good and accurate interpolation data in the optimization modelling of RO plants.

REFERENCES

[1] Seo, J., Kim, Y. M., Chae, S. H., Lim, S. J., Park, H., and Kim, J. H. An Optimization Strategy for a Forward Osmosis-Reverse Osmosis Hybrid Process for Wastewater Reuse and Seawater Desalination: A Modeling Study .*Desalination*, 463, 2019, pp. 40-49 https://doi.org/10.1016/j.desal.2019.03.012

[2] Gómez Palacín, L. Modelling, Simulation and Advanced Control of Small-Scale Reverse Osmosis Desalination Plants. PhD Dissertation, Universidad de Valladolid, Valladoli, Spain, 2014. https://doi.org/10.35376/10324/5583

[3] Susanto-Lee, R. Efficiency Improvements for Small-Scale Reverse-Osmosis Systems. Masters Dissertation, Curtin University, Perth, Australia, 2006. http://hdl.handle.net/20.500.11937/286

[4] Khayet, M., Cojocaru, C., and Essalhi, M. Artificial Neural Network Modeling and Response Surface Methodology of Desalination by Reverse Osmosis. *Journal of Membrane Science*, 368, 2011, pp. 202-214 https://doi.org/10.1016/j.memsci.2010.11.030

[5] Gu, B., Xu, X. Y. and Adjiman, C. A Predictive Model for Spiral Wound Reverse Osmosis. *Environment*, 333, 2016, pp. 712-717 https://doi.org/10.1016/j.compchemeng.2016.07.029

[6] Marriott, J., Sørensen, E., and Bogle, I. Detailed Mathematical Modelling of Membrane Modules. *Computers & Chemical Engineering*, 25, 2001, pp. 693-700 https://doi.org/10.1016/S0098-1354(01)00670-6

[7] Abbas, A. and Al-Bastaki, N. Modeling of an RO Water Desalination Unit Using Neural Networks. *Chemical Engineering Journal*, 114, 2005, pp. 139-143 https://doi.org/10.1016/j.cej.2005.07.016

[8] Helal, A., El-Nashar, A., Al-Katheeri, E., and Al-Malek, S. Optimal Design of Hybrid RO/MSF Desalination Plants Part I: Modeling and Algorithms . *Desalination*, 154, 2003, pp. 43-66 https://doi.org/10.1016/S0011-9164(03)00207-8

[9] Marcovecchio, M. G., Aguirre, P. A., and Scenna, N. J., Global Optimal Design of Reverse Osmosis Networks for Seawater Desalination: Modeling and Algorithm. *Desalination*, 184, 2005, pp. 259-271 https://doi.org/10.1016/j.desal.2005.03.056

[10] Barello, M., Manca, D., Patel, R., and Mujtaba, I. M. Neural Network Based Correlation for Estimating Water Permeability Constant in Ro Desalination Process under Fouling. *Desalination*, 345, 2014, pp. 101-111 https://doi.org/10.1016/j.desal.2014.04.016

[11] Sarkar, B., Sengupta, A., De, S., and DasGupta, S. Prediction of Permeate Flux During Electric Field Enhanced Cross-Flow Ultrafiltration—a Neural Network Approach. *Separation and Purification Technology*, 65, 2009, pp. 260-268 https://doi.org/10.1016/j.seppur.2008.10.032

[12] Porrazzo, R., Cipollina, A., Galluzzo, M., and Micale, G. A Neural Network-Based Optimizing Control System for a Seawater-Desalination Solar-Powered Membrane Distillation Unit. *Computers & Chemical Engineering*, 54, 2013, pp. 79-96 https://doi.org/10.1016/j.compchemeng.2013.03.015

[13] Bowen, W. R., Jones, M. G., and Yousef, H. N. Dynamic Ultrafiltration of Proteins–a Neural Network Approach. *Journal of Membrane Science*, 146, 1998, pp. 225-235 https://doi.org/10.1016/S0376-7388(98)00108-2

[14] Mirjalili, S. Genetic Algorithm. In Kacprzyk, J. ed., *Evolutionary Algorithms and Neural Networks*.Cham, Springer. 2019, pp. 43-55.

[15] Murthy, Z. and Vengal, J. C. Optimization of a Reverse Osmosis System Using Genetic Algorithm. *Separation Science and Technology*, 41, 2006, pp. 647-663 https://doi.org/10.1080/01496390500526854

[16] Kim, J.-S., Kim, J.-H., Park, J.-M., Park, S.-M., Choe, W.-Y., and Heo, H. Auto Tuning PID Controller Based on Improved Genetic Algorithm for Reverse Osmosis Plant. *World Academy of Science, Engineering and Technology*, 47, 2008, pp. 384-389, https://pdfs.semanticscholar.org/d4b4/d805b67a1f5f98d9ae12a41207b9f09f342a.pdf?_ga =2.224980378.1041034929.1567063440-1540959593.1557738876

[17] Kumar, M., Husian, M., Upreti, N., and Gupta, D. Genetic Algorithm: Review and Application. *International Journal of Information Technology and Knowledge Management*, 2, 2010, pp. 451-454, http://www.csjournals.com/IJITKM/PDF%203-1/55.pdf

[18] Razali, N. M. and Geraghty, J. Genetic Algorithm Performance with Different Selection Strategies in Solving Tsp. In Proceedings of the World Congress on Engineering. 2011.

International Association of Engineers Hong Kong, http://www.iaeng.org/publication/WCE2011/WCE2011_pp1134-1139.pdf

[19] Djebedjian, B., Gad, H., Khaled, I., and Rayan, M. A. Optimization of Reverse Osmosis Desalination System Using Genetic Algorithms Technique. In Twelfth International Water Technology Conference, IWTC12, Alexandria, Egypt. 2008. https://www.researchgate.net/profile/Helmy_Gad/publication/229036049_Optimization_of_reverse_osmosis_desalination_system_using_genetic_algorithms_technique

[20] Gen, M. and Lin, L., Genetic Algorithms. *Wiley Encyclopedia of Computer Science and Engineering*, 2007, pp. 1-15 https://doi.org/10.1002/9780470050118.ecse169

[21] Rout, M., Sain, D., Swain, S., and Mishra, S. PID Controller Design for Cruise Control System Using Genetic Algorithm. In 2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT). 2016. IEEE.10.1109/ICEEOT.2016.7755502

[22] Alatiqi, I., Ettouney, H., and El-Dessouky, H., Process Control in Water Desalination Industry: An Overview. *Desalination*, 126, 1999, pp. 15-32 https://doi.org/10.1016/S0011-9164(99)00151-4

[23] Concha, A., Varadharaj, E., Hernandez-Rivera, N., and Gadi, S. A Novel Implementation Technique for Genetic Algorithm Based Auto-Tuning PID Controller. In 2017 IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI). 2017. IEEE.10.1109/ICPCSI.2017.8391942

[24] Sahib, M. A. and Ahmed, B. S. A New Multiobjective Performance Criterion Used in PID Tuning Optimization Algorithms. *Journal of Advanced Research*, 7, 2016, pp. 125-134 https://doi.org/10.1016/j.jare.2015.03.004

[25] Thomas, N. and Poongodi, D. P. Position Control of Dc Motor Using Genetic Algorithm Based Pid Controller. In Proceedings of the world congress on engineering. 2009. London, UK, http://iaeng.org/publication/WCE2009/WCE2009_pp1618-1622.pdf

[26] Sassi, K.M. and Mujtaba, I.M. Simulation and Optimization of Full Scale Reverse Osmosis Desalination Plant. *Computer Aided Chemical Engineering*, 28, 2010, pp. 895-900.

[27] Song, L., Hong, S., Hu, J., Ong, S., and Ng, W. Simulations of Full-Scale Reverse Osmosis Membrane Process. *Journal of Environmental Eengineering*, 128, 2002, pp. 960-966 10.1061/~ASCE!0733-9372~2002!128:10~960!

[28] Oh, H.-J., Hwang, T.-M., and Lee, S. A Simplified Simulation Model of RO Systems for Seawater Desalination. *Desalination*, 238, 2009, pp. 128-139 https://doi.org/10.1016/j.desal.2008.01.043

CHAPTER 5. Membrane Modeling and Simulation for a Small Scale Reverse Osmosis Desalination Plant

Membranes are the most important components of the RO plant as the main operation happens inside them. Modeling of these membranes is essential and proper simulations and optimization of these components greatly affect the operation of the system. Membrane modeling softwares like Dow powered Reverse Osmosis Software Analysis (ROSA) and the Hydranautics Nitto Group Company powered Integrated Membrane Solutions Design (IMSDesign) were used in the modeling of the membranes. This article was published in the International Journal of Engineering Research and Technology (IJERT).

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Membrane Modeling and Simulation for a Small Scale Reverse Osmosis Desalination Plant

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Abstract

Reverse osmosis (RO) has proven to be the most effective and efficient desalination method in recent years. Modelling and optimization of RO desalination plants is ongoing in order to come up with sustainable and efficient RO plants, leading to several techniques being employed in relation to mathematical models of mass and heat transfer, salt rejection and membrane solute permeability. Membrane designs and specifications are factors that affect the efficiency of the RO desalination system. Membrane design tools and software such as ROSA and IMSDesign, which are provided by the membrane manufacturing companies, help in the selection and authentication of low energy consumption and high salt rejection membranes for the design of desalination units.

Keywords— desalination; reverse osmosis; modeling; simulation

I. Introduction

Reverse osmosis (RO) is a process that occurs when pressure that is greater than the osmotic pressure is applied to a high saline solution (concentrated) through a membrane. Water is pressurized to flow from the high saline side to the diluted side, and dissolved salts are retained by the membrane. Membrane technologies such as RO use high electrical and mechanical energies. Future supplies of conventional energy sources are uncertain. Therefore, for sustainable development purposes, it is imperative to optimize and reduce energy requirements of the existing processes [1]. Of late, substantial membrane technology advancement has resulted in improvements in the quality of filtering processes and reduction of costs [2].

In the current study two membrane software tools were used and compared with each other in the prediction and selection of membranes to be used in the plant. The two software tools used were the Reverse Osmosis System Analysis (ROSA) for FILMTEC™ membranes (DOW Water and Process Solutions) and Integrated Membrane Solutions Design (IMSDesign) (Hydranautics Nitto Group Company).

IMSDesign is described as a comprehensive membrane projection program that allows users to design an RO system based on hydranautics membranes [3]. ROSA on the other hand, is membrane simulation software that uses FILMTEC™ thin film composite membranes and gives excellent performance for a wide variety of applications, including brackish water purification, low-pressure tap water use, seawater desalination, waste treatment and chemical processing [4].

II. Mathematical Modeling of a Reverse Osmosis System

There are two basic approaches in the mathematical modeling of any process. The first approach is the knowledge based approach, which involve theoretical or parametric models based on fundamental and essential knowledge (mechanisms) of the process and the second approach is the empirical or the non-parametric models, which do not involve the knowledge of the fundamental principles governing the process [5]. There are many approaches that have been used to model RO systems. Different scholars and researchers have come up with many models, some of which include the modeling of membranes [6, 7], modeling of RO plants using neural networks [8], and modeling of RO plants using different algorithms [9, 10]. Fig. 1 shows the schematic diagram of an RO plant with a pre-treatment mechanism, and Fig. 2 shows the RO desalination with ERD or pressure exchanger (PX), 1st pass and 2nd pass RO membranes.

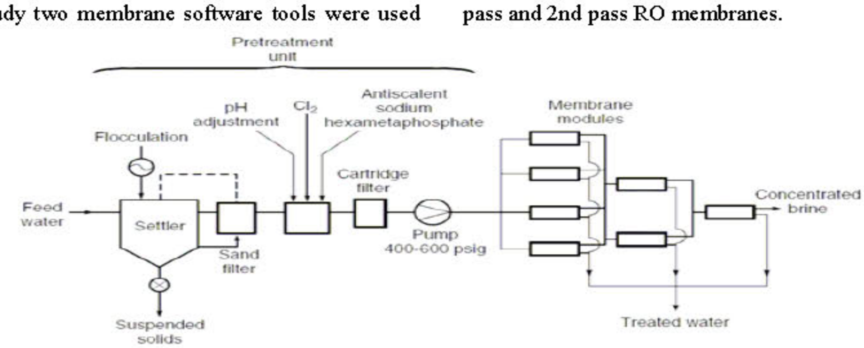

Fig. 1. Schematic diagram of an RO plant with pre-treatment [2]

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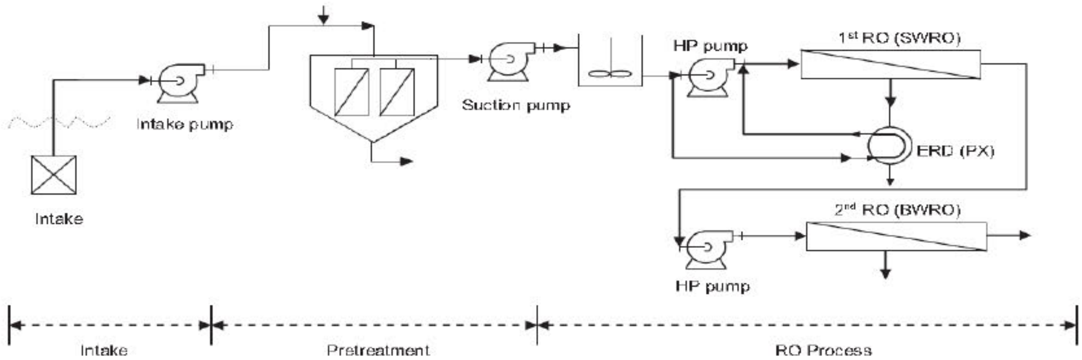

Fig. 2. RO desalination system with ERD/PX module [11]

A. RO System Monitoring

- Pressure and flow are measured at various points in the RO system to ensure proper function.
- Conductivity is used to monitor the removal of solute by the RO system. Conductivity describes the ability of the water to conduct electrical charge. If more dissolved solute is present, water will conduct electricity more readily.
- The conductivity of product water from the RO is monitored continuously during RO operation and often displayed as total dissolved solids or TDS.
- The percent rejection of an RO system describes the ability of the system to remove solute, thus reducing conductivity in the product water, and can be thought of as the percentage of solute that was removed from the water during reverse osmosis. The percent rejection is calculated using (1):

$$\%\ rejection = \frac{Feed\ water\ conductivity - Product\ water\ conductivity}{Feed\ water\ conductivity} * 100\% \quad (1)$$

Modern RO systems will monitor and display the percent rejection in real time during operation. There is no absolute value that is desirable for the percent rejection. Rather, the dialysis facility should use the percent rejection to monitor the efficiency of the RO over time. Percent recovery (also known as the water conversion factor) can be used to monitor the performance of the RO system. The percent recovery can be calculated using (2), where Q is the flow rate:

$$\%recovery = \frac{Q_{permeate}}{Q_{permeate} + Q_{reject}} * 100\% \quad (2)$$

The percent recovery does not inform water quality, but it is useful for trending the performance of the RO membrane. Membranes that become fouled over time will drop their percent recovery. Permeate flow rate can also vary due to changes in pressure and temperature. For example, a seasonal decrease in water temperature would be expected to decrease the percent recovery. The various measures of RO function—pressure, flow, conductivity, % rejection, % recovery, etc.—should be recorded in a daily treatment log for regular review and trending analysis.

Table I is a summary of the quality and typical characteristics of sea water found in different areas of South Africa [13, 14]. Table II shows the main constituents of standard seawater and their respective concentrations, and Table III shows the analysis of seawater near Cape Town, West Coast region.

TABLE I. AVERAGE FEED WATER TEMPERATURE AND TOTAL DISSOLVED SOLIDS (TDS) IN MILLIGRAMS/LITRE (MG/L) FOR DIFFERENT LOCATIONS IN SOUTH AFRICA

Location of raw water type	Feed water TDS (mg/l)	Feed water temperature (^{0}C)
West Coast	> 35 000	9 to 14
South Coast	35 000 to 35 400	16 to 21
East Coast	34 700 to 35 400	21 to 25

Where: East Coast stretches from East London up to the Mozambican boarder, South Coast stretches from East London to Cape Agulhas and the West Coast is a region that stretches from Cape Agulhas to the mouth of the Orange river [13]

TABLE II. STANDARD SEA WATER MAIN CONSTITUENTS AND THEIR RESPECTIVE CONCENTRATIONS [14]

Constituent	Concentration (mg/l)
Sodium Na^+	10 561
Magnesium, Mg^{2+}	1 272
Calcium, Ca^{2+}	400
Potassium, K^+	380
Chloride, Cl^-	18 980
Sulphate, SO_4^{2-}	2 649
Bicarbonate, HCO_3^{2-}	142
Bromide, Br^-	65
Other solids	34
Density (20 °C)	1.0243 s.g.

TABLE III. SEA WATER MAIN CONSTITUENTS OFF THE WEST COAST, NEAR CAPE TOWN [14]

Total Dissolved Solids (mg/litre)	35 644
Sodium (as Na mg/litre)	10 957
Magnesium (as Mg mg/litre)	1 312
Potassium (as K mg/litre)	393
Calcium (as Ca mg/litre)	406

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Chloride (as Cl mg/litre)	19 677
Sulphate (as SO4 mg/litre)	2 757
Alkalinity (as CaCO3 mg/litre)	117
Fluoride (as F mg/litre)	1.1
Cyanide (as CN mg/litre)	< 0.05
Dissolved Organic Carbon (mg/litre)	< 1
Conductivity (µS/cm) @ 25 °C	51 000
pH (Lab)	8.1
Hardness (as CaCO3 mg/litre)	6 417
CATIONS (meq/litre)	614.87
ANIONS (meq/litre)	614.82
Suspended Solids (mg/litre) (No. 1 filter)	3.7
Suspended Solids (mg/litre) (0.45 µm)	1.5
Turbidity (NTU)	6.5

B. RO Model Equations

The following section is a summary of the RO model equations [15]:

Permeate flux, Jw:

$$J_w = A_w(\Delta P - \Delta\pi) \quad (3)$$

$$J_w = \frac{Q_p}{A_{mem}} \quad (4)$$

Salt rejection, R_s:

$$R_s = [1 + \frac{B_s}{A_w(\Delta\rho - \Delta\pi)}]^{-1} \quad (5)$$

Also, salt rejection, R_s, can be calculated by [14]:

$$R_s = 1 - \frac{TDS_p}{TDS_f} \quad (6)$$

Osmotic pressure, $\Delta\pi$:

$$\Delta\pi = RT\sum\frac{n}{v} \quad (7)$$

Specific energy consumption, SEC:

$$EC = \frac{P_f Q_f (E_{pump})^{-1} - P_r Q_r E_{ERD}}{Q_p} \quad (8)$$

Recovery ratio, R:

$$R = \frac{Q_p}{Q_f} \quad (9)$$

Assuming no softening is done, the following calcium salts may typically limit recovery:

Calcium carbonate (calcite) at a feed pH of 7, R_{CaCO3}:

$$R_{CaCO_3} \approx 1 - \frac{\sqrt{Alk * C_{Ca}}}{2000} \quad (10)$$

Calcium sulphate (gypsum), R_{CaSO4}:

$$R_{CaSO_4} \approx 1 - \frac{\sqrt{C_{SO_4} * C_{Ca}}}{2500} \quad (11)$$

Calcium fluoride, R_{CaF2}:

$$R_{CaF_2} \approx 1 - \frac{[(C_F)^2 * C_{Ca}]^{0.33}}{40} \quad (12)$$

Total mass balance:

$$Q_f C_f = Q_p C_p - Q_r C_r \quad (13)$$

Transmembrane pressure difference, ΔP:

$$\Delta P = \frac{P_f + P_r}{2} - P_p \quad (14)$$

Normalised specific energy, SEC*:

$$SEC^* = \frac{SEC}{\Delta\pi} \quad (15)$$

Actual permeate hourly flow rate, Q_h, [14]:

$$Q_h = \frac{Q_d}{24 * \alpha} \quad (16)$$

Total membrane area, A_{mem}:

$$A_{mem} \approx \left(\frac{1000 * Q_h}{\emptyset_1}\right) + z\left(\frac{1000 * Q_h}{\emptyset_2}\right) \quad (17)$$

Feed pressure at a given temperature, P_f:

$$P_f \approx \frac{0.00076 * TDS_f}{1 - R} + \left(\frac{\emptyset}{\varepsilon} + 5\right) * 1.034^{25-T} \quad (18)$$

Mass transfer coefficient, k_i [11]:

$$k_i = 0.5510\left(\frac{ud_h}{v}\right)^{0.4}\left(\frac{v}{D_i}\right)^{0.17}\left(\frac{c_{b,i}}{\rho}\right)^{-0.77} \quad (19)$$

Desalination energy, E_{desal}, other additional energy, E_{other}, and the total energy required for the entire RO process, ET [1, 14]:

$$E_{desal} = \left[\frac{Q_h * P_f}{36 * R * \eta_p}\right] - s\left[\frac{Q_h(P_f - 5)(1 - R)}{36 * R * \eta_r}\right] \quad (20)$$

$$E_{other} \approx \left[\frac{Q_h * P_f}{36 * \eta}\right] \quad (21)$$

$$E_T = E_{desal} + E_{ERD} + E_{other} \quad (22)$$

The specific energy required per volume of permeate water, E_{spec}:

$$E_{spec} = \frac{E_T}{Q_h} \quad (23)$$

Maximum possible TDS of reject, TDS_r:

$$TDS_r = \frac{TDS_f}{1 - R} \quad (24)$$

The equations for the modeling of the UF unit are summarized below [16].

Normalized Temperature, TMP*:

$$TMP^* = TCF * TMP \quad (25)$$

Temperature correction factor (TCF), which is a factor that takes into consideration the effect of the temperature, T (°C) and its influence on the viscosity of water:

$$TCF = \frac{10^{\left(\frac{247.8}{25+273.16-140}\right)}}{10^{\left(\frac{247.8}{T+273.16-140}\right)}} \quad (26)$$

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Different TMP values obtained at different temperatures can be compared and transported to the same reference temperature of 25 °C [17].

Efficiency of the UF process, which is defined as the net yield of the UF process:

$$Efficiency = Availability * Recovery \quad (27)$$

Availability, which is the measure of the time the UF module is producing water:

$$Availability = \frac{t_f}{t_r} \quad (28)$$

Recovery, which is the measure of the net water produced:

$$Recovery = \frac{V_f - V_{CEB} - V_{BW}}{V_f} \quad (29)$$

Hourly feed capacity of the pre-treatment plant, $Q_{h(in)}$ [14]:

$$Q_{h(in)} = \frac{Q_h}{R(1-\beta)} \quad (30)$$

C. Theoretical Values of RO Parameters

Specific energy consumption (SEC) is the amount of energy consumed per unit freshwater produced (kJ/kg) and recovery ratio, and r (%) is the volume of freshwater produced per unit volume of the seawater fed. Fig. 3 shows the graph of theoretical minimum energy consumed against the recovery ratio [1].

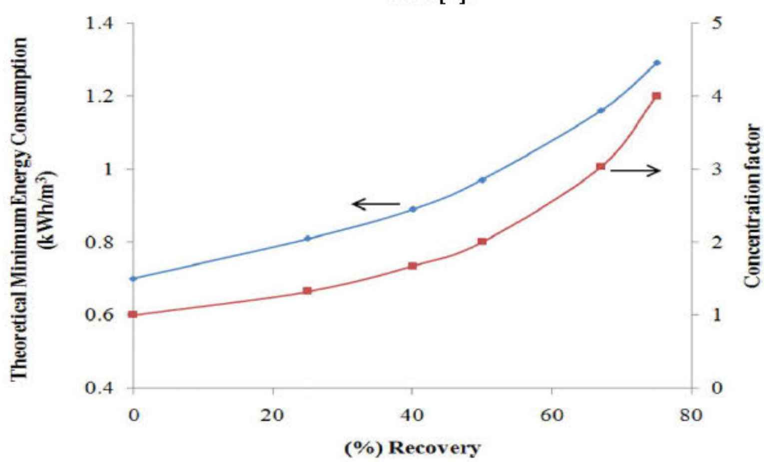

Fig. 3. Theoretical minimum energy consumed against the recovery ratio [1]

1) Energy Recovery Devices

There are four types of energy recovery devices (ERDs) that can be used in RO process. These are pelton turbines, hydraulic turbochargers, pressure exchangers and work exchangers. Table IV shows the characteristics of three of these ERDs [1].

TABLE IV. CHARACTERISTICS OF THREE TYPES OF ERDS [1]

Characteristic	Pelton turbine	Turbocharger	Isobaric energy recovery device (work exchanger)
Working principle	Centrifugal mode	Centrifugal mode	Positive displacement
Overall net energy transfer efficiency	Energy transfer from hydraulic to mechanical; 80% (70–80%)	Energy transfer from hydraulic to hydraulic; 83%	Energy transfer from hydraulic to hydraulic; 95%
Effect of deviation from design point	Wide operating range	Wide operating range	Moderate impact on performance
Discharge	Atmospheric	Pressurized	pressurized
Capital cost	Low	Moderate	High (250% higher than Pelton turbine)
Pumping requirements	Connected directly to SWRO pump/motor, requires full sized SWRO pump/motor		Small size SWRO/pump motor required to pump permeate volume only, requires small booster pump/motor
Material of construction	Metallic construction	Metallic construction	Available in non-metallic construction for corrosion resistance
Specific energy consumption	2.44–4.35 (kWh/m^3)	2.42–4.29 (kWh/m^3)	1.93–2.85 (kWh/m^3)
Capacity	Multi MGD	< 2.5 MGD	<2.5 MGD
Foot print	Compact	Compact	Large

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III. System Modeling

A. Design Modeling

Fig. 4 shows the design methodology used for the design of the single stage SWRO desalination unit.

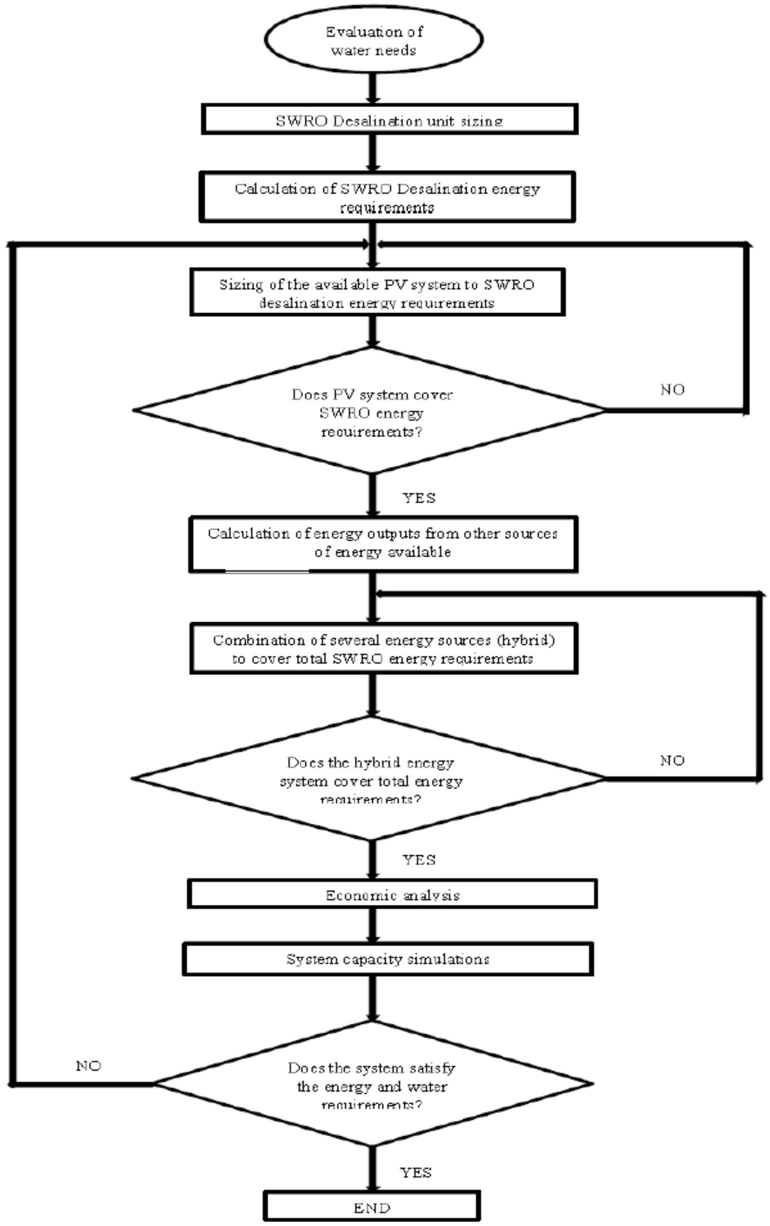

Fig. 4. Flow diagram for SWRO desalination unit

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B. Permeate Flow Rate and Actual Permeate Hourly Flow Rate (Q_h)

The desired permeate flow rate of the plant is 10 m3/d. The actual permeate hourly flow rate, assuming 8 % idle time or 92 % availability of the plant, is 0.45 m3/h.

C. Recovery Rate (R)

The typical recovery rate design guideline for the desalination of seawater is about 0.4 or 40 %, assuming no softening of feed water is performed.

D. Feed Flow rate (Q_f)

Assuming R = 0.4 and Q_p = 10 m^3/d, the design feed flow rate is 25 m^3/d.

E. Feed and Permeate Total Dissolved Salts Concentrations (TDSp and TDSf)

Total dissolved solids of feed water, TDS_f, is approximately 35 600 mg/l, the desired design total dissolved solids of permeate water; TDS_p is less than 500 mg/l.

F. Salt Rejection

Salt rejection, Rs, is calculated and found to be around 0.99 or 99 %.

G. Operating Temperature (T)

Water becomes less viscous at higher temperatures, hence the need for a generally high feed operating temperature. The proposed feed operating temperature is in the range of 25 °C to 30 °C. The design temperature for this system is 25 °C.

H. Energy Recovery Devices (ERD) and Power Exchangers (PX)

Research and design has shown that multi-stage systems, with modules connected to reject water with booster pumps, are able in principle to minimize electricity consumption. This system will have no energy recovery devices.

I. Maximum Possible TDS of reject, (TDS_r)

The calculated maximum possible TDS of reject is 59 406 mg/l.

Input parameters are shown in Table V.

IV. Computer Simulation of the RO Simulation

Computer simulations for the RO system were carried out using two different membrane design software tools to analyze the performance of the RO system and to ascertain the calculations above. ROSA and IMSDesign software tools were used. The results obtained from the two tools were compared and the software with the results that showed greatest similarities to the desired output was selected for further manipulation and optimization of the RO process. The software tools also helped in the selection of suitable membranes for the desired output.

A. Simulation Results

According to several simulation processes carried out for small scale SWRO desalination plants, a single stage RO system was discovered to be much more economical and energy efficient compared to a two-stage or multi-stage system. Capital costs and power requirements were slightly lower in a single stage than in a two-stage system for comparable permeate water quality. In this regard, a single stage SWRO desalination system was chosen and the above selected/assumed parameters were captured in the two simulation software tools and the following results were obtained.

B. IMSDesign Results

Seawater quality inputs tabulated in Table III and the selected/assumed parameters in Table V were fed into the IMSDesign software as shown in Fig. 5. A summary of the results is shown in Fig. 6 and the detailed report of the results of the simulations is shown in Appendix 1 at the end of this document.

TABLE V. SUMMARY OF THE CALCULATED, ASSUMED/SELECTED PARAMETERS TO BE SET AS INPUT PARAMETERS FOR THE PERFORMANCE ANALYSIS OF THE RO SYSTEM

Parameter	Calculated value	Assumed/ Selected	Equation
pH (Lab)		8.1	Table 3
Permeate flow rate		10 m^3/d	-
Recovery rate		0.4	-
Actual permeate hourly flow rate	0.45 m^3/h		(16)
Salt rejection	0.99		(6)
Operating temperature		25 °C	-
Feed TDS		35 644 mg/l	Table 3
Permeate TDS		< 500 mg/l	-
Maximum possible TDS of reject	59 406 mg/l		(24)

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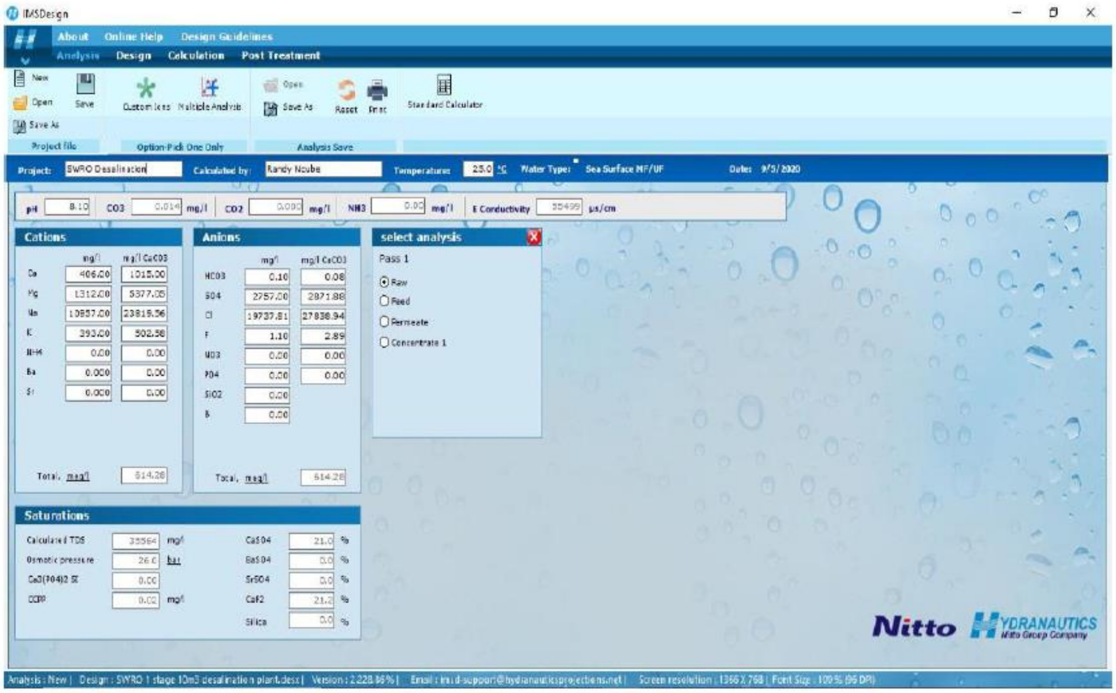
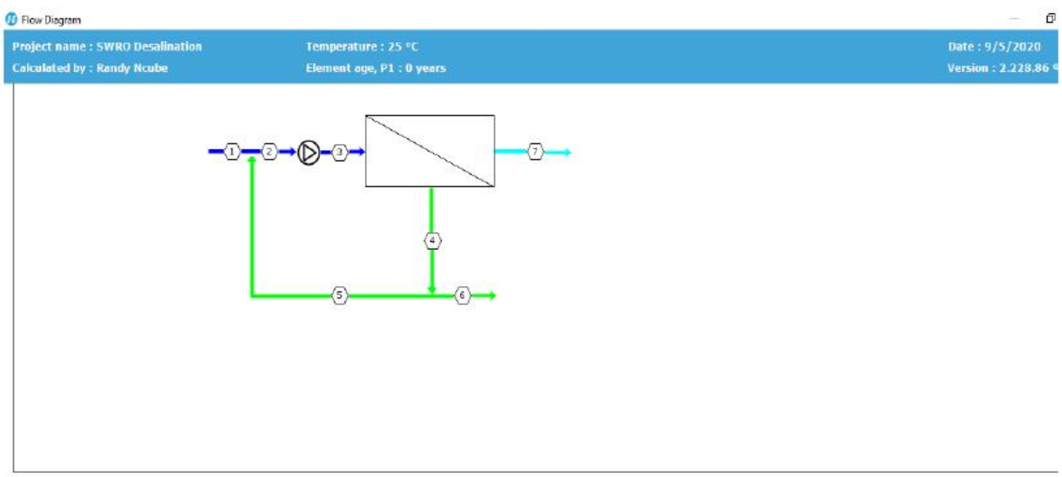


Fig. 5. Input parameters on the IMSDesign software



	1	2	3	4	5	6	7
Flow (m3/h)	1.12	1.17	1.17	0.720	0.050	0.670	0.450
Pressure (bar)	0	0	49.6	49.3	0	0	0
TDS (mg/l)	35564	36568	36568	59047	59047	59047	324
pH	8.10	8.10	8.10	8.13	8.13	8.13	6.80
Econd (µs/cm)	55499	56974	56974	89596	89596	89596	704

Fig. 6. A systems configuration obtained after running the IMSDesign program

C. ROSA Results

Seawater quality inputs tabulated in Table III and the selected/assumed parameters in Table V were fed into the ROSA software as shown in Fig. 7. A summary of the results is shown in Fig. 8 and the detailed report of the results of the simulations is shown in Appendix 2 at the end of this document.

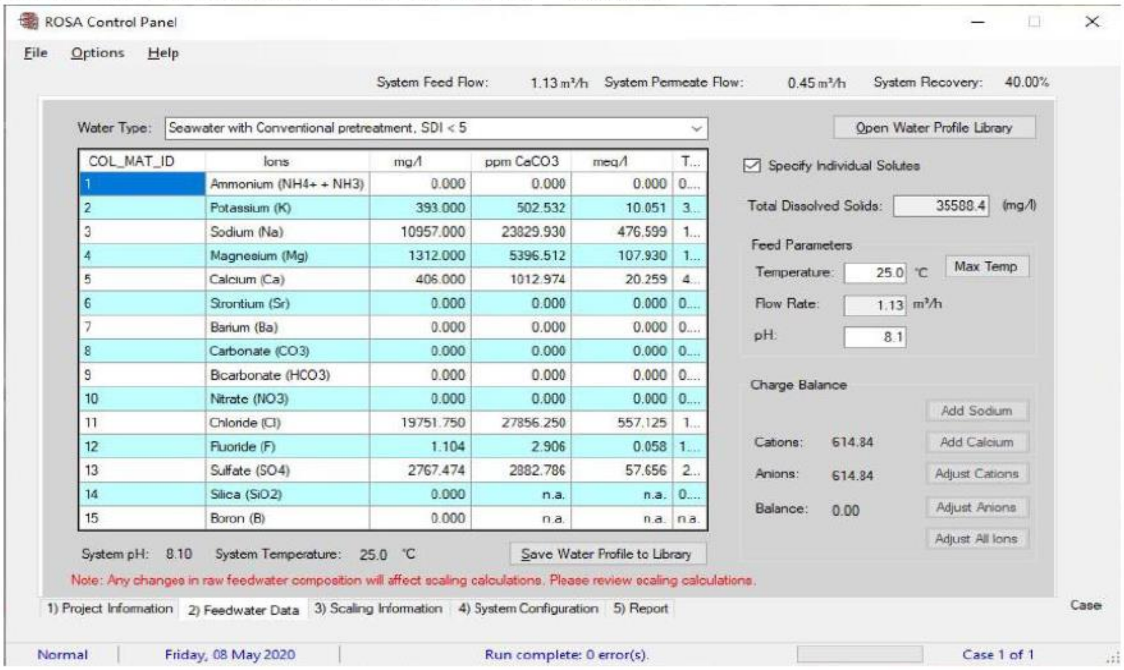


Fig. 7. Input parameters on the ROSA software

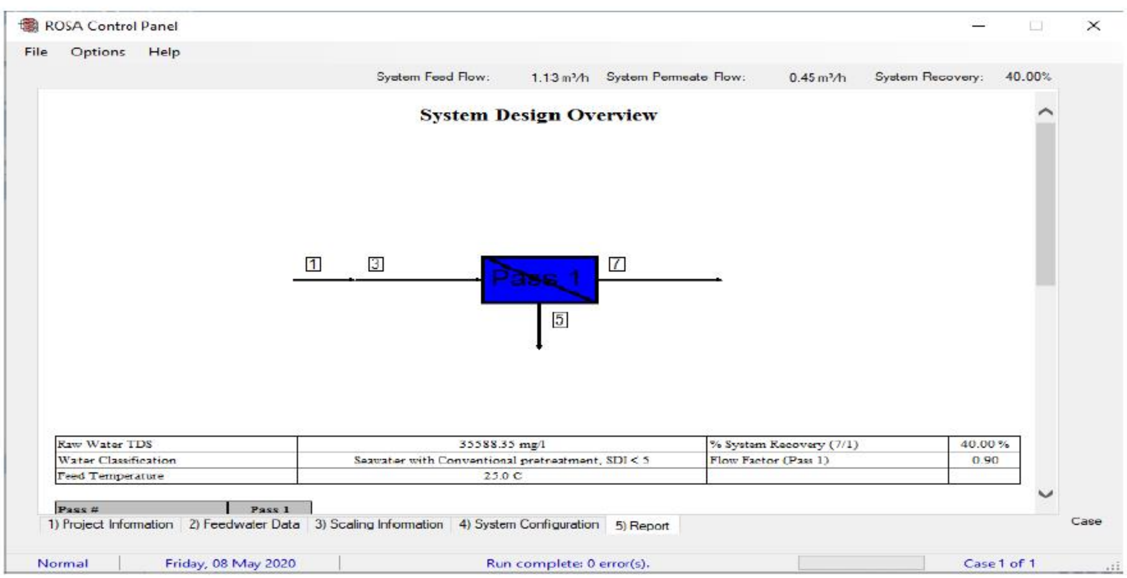


Fig. 8. A system design overview and summary of the ROSA program

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V. Results Analysis

The following section is meant to analyze the results from the two membrane software tools to select the most feasible system for further analysis and optimization of the system.

A. Results Comparison

Table VI shows the results from the two software tools obtained after running the programs with the same inputs.

TABLE VI. RESULTS OF THE IMSDESIGN AND ROSA SOFTWARE

	IMSDesign	ROSA
Permeate TDS (mg/l)	324.5	633.3
Average flux rate (lmh)	15.1	14.42
Feed pressure (bars)	49.6	47.44
Average specific energy (kW/h)	5.12	3.66
Membrane type	SWC5-LD-4040	SW30-2540
Total number of elements	4	12

TABLE VII. COMPARISON OF MEMBRANE CHARACTERISTICS

	SWC5-LD-4040	SW30-2540
Manufacturer	Hydranautics SWC membranes	Dow Filmtec
Material	Composite polyamide	Polyamide thin-film composite
Nominal Production (m^3/d)	6.62	2.6
Salt Rejection (%)	99.7	99.4
Size (m * m)	0.1 * 1	
Active Area (m^2)	2	2.6
Max. Applied Pressure (bars)	82.7	69
pH	2 to 11	2 to 11
Max. Operating Temp. (°C)	45	45
Price/membrane (USD)	269	244
Total Number of membrane elements	4	12
Total membrane costs (USD)	1076	2928
Advantages	-High productivity and salt rejection rates, optimized flow, low fouling and low energy consumption; -Optimum salt rejection and permeate flows at low operating pressures; -High energy efficiency at low costs, low treatment cost while offering extreme durability and consistent performance.	-High flux reduces energy use or pressure required; -Good salt rejection results in good quality water.

B. Selected Design Setup

Although both the IMSDesign and ROSA desalination design tools showed certain individual advantages, there are two factors that led to the selection of the design setup to be used for optimization. These factors include the permeate TDS and the capital (setup) costs (particularly the cost of membranes). The desired output for the permeate TDS in this design was < 500 mg/l according to WHO standards for potable water for human consumption [2]. From the number of membranes elements required to set up the plant, the setup costs could be calculated and determined. From the above factors, the simulation conducted using the IMSDesign suited the design for this project.

VI. Conclusion

A clear analytical mathematical model and membrane simulations using ROSA and IMSDesign software tools was used for the performance predictions of the type of membrane module and consequently for the performance of the RO plant. The IMSDesign setup showed that the setup cost was lower than that of the ROSA software whereas the specific energy of the ROSA setup was lower than that of IMSDesign setup. The IMSDesign setup also showed that the required design output of less than 500 mg/l permeate TDS could be obtained. A pilot plant will be built based on the selected RO setup and will be used in the optimization of the complete system through experimentation so as to reduce specific energy, thereby reducing the running costs. Experiments on the effect of temperature and pressure variation on energy consumption of the pilot plant will be carried out and the optimum conditions will be employed. Optimization and simulation of the RO plant control system using Matlab Simulink will be performed so as to improve energy consumption without compromising the permeate water quality.

Nomenclature

A_{mem} Total membrane area, m^2

A_W - Permeability coefficient, m/s.Pa

B_s - Solute transport parameter, m/s

E - Specific energy consumption, kWh/m^3

E_{ERD} Turbine energy, kWh

E_{pump} Pump energy consumption, kWh

E_{spec} The specific energy required per volume of permeate water, kWh/m^3

J_W - Permeate flux, m/s

ΔP - Pressure difference across the membrane, Pa

P_f - Feed water pressure, Pa

P_p - Permeate pressure, Pa

P_r - Rejected pressure, Pa

Q_f - Feed flow rate, m3/d

Q_h - Permeate hourly flow rate, m3/h

Q_p - Permeate flow rate, m3/d

$Q_{p,el}$ Permeate flow rate per membrane element, m3/s

Q_p Mass flow rate of permeate in one element, kg/s

Q_r - Rejected flow rate, m^3/d

Q_{bypass} -Amount of water mixes with the permeate to achieve the required salinity, m^3

R - Gas constant, J/mol-k

R_s - Salt rejection, %

s - The selection parameter, s = 1 if an energy recovery unit is installed, and s = 0 if no recovery unit is installed

T - Temperature, °C

V_w - Water molar volume, m^3

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$\dot{W}$ - Work, kW

E_T - Total energy requirement, kW

E_{in} - Energy required to draw the feed water from the source, kW

E_{pt} - Energy required for pre-treatment and post treatment (micro filtration and pumping), kW

E_{hp} - Energy required by high pressure pump, kW

E_{other} Energy required by other accessories (chemical dosing, filter backwashing/cleaning and pumping the product water), kW

t_f - Filtration time, h

t_t - Total time, h

V_f - Volume of filtrate, m^3

V_{CEB} Volume of chemically enhanced backwash, m^3

V_{BW} Volume of backwash, m^3

z - Selection factor, one for a double pass system, or zero for a single-pass system

$\Delta\pi$ - Osmotic pressure, Pa

α - Availability

ϕ - Average flux (l/h.m^2)

ε - Membrane type and its flux per driving pressure

β - Fraction feed water lost at the pre-treatment plant (typically between 3 % and 15 %, depending on the process)

η_p - Pump efficiency (typically around 0.75)

η_r - Efficiency of the energy recovery unit (if installed)

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References

[1] V.G. Gude, "Energy consumption and recovery in reverse osmosis" Desalin. Water Treat., 36(1-3), pp. 239-260, 2011. DOI: https://doi.org/10.5004/dwt.2011.2534.

[2] S. Syafiie, L. Palacin, C. De Prada, and F. Tadeo. "Membrane modeling for simulation and control of reverse osmosis in desalination plants." in Proceedings of the UKACC International Conference on Control, 2008.

[3] Solution Design, IMSDesign, Inge "Watertechnologies wins another major contract in China, Membr. Technol., 2008 DOI: https://doi.org/10.1016/S0958-2118(08)70232-5.

[4] DuPont Water Solutions, Filmtec™ Reverse Osmosis Membranes. Technical Manual, Form, (609-00071): 2020. Available: https://www.dupont.com/content/dam/dupont/amer/us/en/water-solutions/public/documents/en/45-D01504-en.pdf

[5] M. Khayet, C. Cojocaru, and M. Essalhi, "Artificial neural network modeling and response surface methodology of desalination by reverse osmosis," J. Membr. Sci., 368(1-2), pp. 202-214, 2011. DOI: https://doi.org/10.1016/j.memsci.2010.11.030.

[6] B. Gu, G.Y. Xu, and C.S. Adjiman, "A predictive model for spiral wound reverse osmosis membrane modules: The effect of winding geometry and accurate geometric details," Comput. Chem. Eng., 96, pp. 248-265, 2017. DOI: https://doi.org/10.1016/j.compchemeng.2016.07.029.

[7] J. Marriott, E. Sørensen, and I. Bogle, "Detailed mathematical modelling of membrane modules," Comput. Chem. Eng., 25(4-6), pp. 693-700, 2001. DOI: https://doi.org/10.1016/S0098-1354(01)00670-6.

[8] A. Abbas, and N. Al-Bastaki, "Modeling of an RO water desalination unit using neural networks," Chem. Eng. J., 114(1-3), pp. 139-143, 2005. DOI: https://doi.org/10.1016/j.cej.2005.07.016.

[9] A. Helal, A. El-Nashar, E. Al-Katheeri, and S. Al-Malek, "Optimal design of hybrid RO/MSF desalination plants Part I: Modeling and algorithms," Desalination, 154(1), pp. 43-66, 2003. DOI: https://doi.org/10.1016/S0011-9164(03)00207-8.

[10] M.G. Marcovecchio, P.A. Aguirre, and N.J. Scenna, "Global optimal design of reverse osmosis networks for seawater desalination: modeling and algorithm. Desalination, 184(1-3), pp. 259-271, 2005. DOI: https://doi.org/10.1016/j.desal.2005.03.056.

[11] J.-S. Choi, and J.-T. Kim, "Modeling of full-scale reverse osmosis desalination system: Influence of operational parameters" J. Ind. Eng. Chem., 21, pp. 261-268, 2015. DOI: https://doi.org/10.1016/j.jiec.2014.02.033.

[12] S. Bieber, "Water treatment equipment for in-center hemodialysis" in Handbook of Dialysis Therapy. Amsterdam: Elsevier, 2017, pp. 123-143.

[13] C. Swartz, J. Du Plessis, A. Burger, and G. Offringa, "A desalination guide for South African municipal engineers," Water SA, 32(5), 2006 DOI: https://doi.org/10.4314/wsa.v32i5.47845.

[14] J. Du Plessis, A. Burger, C. Swartz, and N. Musee, A Desalination Guide for South African Municipal Engineers. Pretoria: Water Research Commission, 2006. Available: http://www.coastkzn.co.za/wp-content/uploads/2019/02/desalination-Guideline-for-ENGINEERS-WRC.pdf.

[15] M.S. Atab, A. Smallbone, and A. Roskilly, "An operational and economic study of a reverse osmosis desalination system for potable water and land irrigation," Desalination, 397, pp. 174-184, 2016. DOI: https://doi.org/10.1016/j.desal.2016.06.020.

[16] G. Gilabert-Oriol, M. Hassan, J. Dewisme, V. Garcia-Molina, and M. Busch, "Backwashing pressurized ultrafiltration using reverse osmosis brine in seawater desalination and its potential costs savings," Desalin. Water Treat., 55(10), pp. 2800-2812, 2015. pp. 2800-2812 DOI: https://doi.org/10.1080/19443994.2014.939491.

[17] G. Gilabert Oriol, M. Hassan, J. Dewisme, M. Busch, and V. Garcia-Molina, "High efficiency operation of pressurized ultrafiltration for seawater desalination based on advanced cleaning research. Ind. Eng. Chem. Res., 52(45), pp. 15939-15945, 2013. DOI: https://doi.org/10.1021/ie402643z.

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APPENDIX 1 – IMSDesign Results

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Water Analysis : Raw Pass 1

Project name	SWRO Desalination
Water source	Sea Surface MF/UF

pH	8.10	
E.cond	55499.0	μs/cm
CO2	0.000	mg/l
NH3	0.000	mg/l
Temperature	25.0	°C
TDS	35564	mg/l

Ion	mg/l	mg/l CaCO3
Ca	406.00	1015.00
Mg	1312.00	5377.05
Na	10957.00	23819.56
K	393.00	502.58
NH4	0.00	0.00
Ba	0.000	0.00
Sr	0.000	0.00
	Total, meq/l	614.28

Ion	mg/l	mg/l CaCO3
CO3	0.014	0.02
HCO3	0.10	0.08
SO4	2757.00	2871.88
Cl	19737.81	27838.94
F	1.10	2.89
NO3	0.00	0.00
PO4	0.00	0.00
SiO2	0.00	0.00
B	0.00	0.00
	Total, meq/l	614.28

Saturations Information

CaSO4 / KSP * 100	21 %
BaSO4 / KSP * 100	0 %
SrSO4 / KSP * 100	0 %
CaF2 / KSP * 100	21 %
SiO2 saturation	0 %
Ca3(PO4)2 saturation index	0
CCPP, mg/l	0.02
Ionic strength	0.707
Osmotic pressure	26.02 bar

Integrated Membranes Solutions Design Software, 2018

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Nitto HYDRANAUTICS Nitto Group Company

Concentrate Recirculation

Project name	SWRO Desalination			Page : 1/6
Calculated by	Randy Ncube		Permeate flow/train	0.45 m3/h
HP Pump flow		1.17 m3/h	Raw water flow/train	1.12 m3/h
Feed pressure		49.6 bar	Permeate recovery	38.46 %
Feed temperature		25.0 °C(77.0°F)	Total system recovery	40.00 %
Concentrate recirculation		0.05 m3/h	Element age	0.0 years
Feed water pH		8.10	Flux decline %, per year	5.0
Chem dose, mg/l, -		H2SO4	Fouling factor	1.00
Specific energy		5.12 kwh/m3	SP increase, per year	7.0 %
Pass NDP		14.3 bar		
Average flux rate		15.1 lmh		
			Feed type	Sea Surface MF/UF

Pass - Stage	Perm. Flow m3/h	Flow / Vessel Feed m3/h	Flow / Vessel Conc m3/h	Flux lmh	DP bar	Flux Max lmh	Beta	Stagewise Pressure Perm. bar	Stagewise Pressure Boost bar	Stagewise Pressure Conc bar	Perm. TDS mg/l	Element Type	Element Quantity	PV# x Elem #
1-1	0.4	1.2	0.7	15.1	0.3	25.1	1.06	0	0	49.3	324.5	SWC5-LD-4040	4	1 x 4M

Ion (mg/l)	Raw Water	Feed Water	Permeate Water	Concentrate 1
Hardness, as CaCO3	6392.05	6573.67	14.302	10642.0
Ca	406.00	417.54	0.908	675.9
Mg	1312.00	1349.28	2.936	2184.3
Na	10957.00	11265.68	117.487	18180.1
K	393.00	404.04	5.265	651.4
NH4	0.00	0.00	0.000	0.0
Ba	0.000	0.000	0.000	0.0
Sr	0.000	0.000	0.000	0.0
H	0.00	0.00	0.000	0.0
CO3	0.01	0.01	0.000	0.0
HCO3	0.10	0.10	0.002	0.1
SO4	2757.00	2835.32	6.680	4589.7
Cl	19737.81	20294.45	191.023	32763.2
F	1.10	1.13	0.021	1.8
NO3	0.00	0.00	0.000	0.0
PO4	0.00	0.00	0.000	0.0
OH	0.13	0.13	0.001	0.2
SiO2	0.00	0.00	0.000	0.0
B	0.00	0.00	0.000	0.0
CO2	0.00	0.00	0.00	0.00
NH3	0.00	0.00	0.00	0.00
TDS	**35564.02**	**36567.55**	**324.32**	**59046.63**
pH	**8.10**	**8.10**	**6.80**	**8.13**

Saturations	**Raw Water**	**Feed Water**	**Concentrate**	**Limits**
CaSO4 / ksp * 100, %	21	22	40	400
SrSO4 / ksp * 100, %	0	0	0	1200
BaSO4 / ksp * 100, %	0	0	0	10000
SiO2 saturation, %	0	0	0	140
CaF2 / ksp * 100, %	21	23	130	50000
Ca3(PO4)2 saturation index	0.0	0.0	0.0	2.4
CCPP, mg/l	0.02	0.02	0.03	850
Ionic strength	0.71	0.73	1.17	
Osmotic pressure, bar	26.0	26.8	43.2	

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Concentrate Recirculation

Project name	SWRO Desalination			Page : 2/6	
Calculated by	Randy Ncube		Permeate flow/train	0.45	m3/h
HP Pump flow		1.17 m3/h	Raw water flow/train	1.12	m3/h
Feed pressure		49.6 bar	Permeate recovery	38.46	%
Feed temperature		25.0 °C(77.0°F)	Total system recovery	40.00	%
Concentrate recirculation		0.05 m3/h	Element age	0.0	years
Feed water pH		8.10	Flux decline %, per year	5.0	
Chem dose, mg/l, -		H2SO4	Fouling factor	1.00	
Specific energy		5.12 kwh/m3	SP increase, per year	7.0	%
Pass NDP		14.3 bar			
Average flux rate		15.1 lmh			
			Feed type	Sea Surface MF/UF	

Pass-Stage	Perm. Flow m3/h	Flow / Vessel Feed m3/h	Flow / Vessel Conc m3/h	Flux lmh	DP bar	Flux Max lmh	Beta	Stagewise Pressure Perm bar	Stagewise Pressure Boost bar	Stagewise Pressure Conc bar	Perm. TDS mg/l	Element Type	Element Quantity	PV# x Elem #
1-1	0.4	1.2	0.7	15.1	0.3	25.1	1.06	0	0	49.3	324.5	SWC5-LD-4040	4	1 x 4M

Pass-Stage	Element no.	Feed Pressure bar	Pressure Drop bar	Conc Osmo. bar	NDP bar	Permeate Water Flow m3/h	Permeate Water Flux lmh	Beta	TDS	Permeate (Stagewise cumulative) Ca	Mg	Na	Cl
1-1	1	49.6	0.1	31.7	18.9	0.2	25.1	1.06	162.5	0.455	1.47	58.885	95.729
1-1	2	49.5	0.07	36.4	13.8	0.1	17	1.05	208.6	0.584	1.887	75.573	122.862
1-1	3	49.4	0.06	40.2	9.9	0.1	11.2	1.04	262.8	0.736	2.378	95.203	154.783
1-1	4	49.3	0.05	43.2	6.8	0.1	7.3	1.03	324.5	0.909	2.937	117.54	191.11

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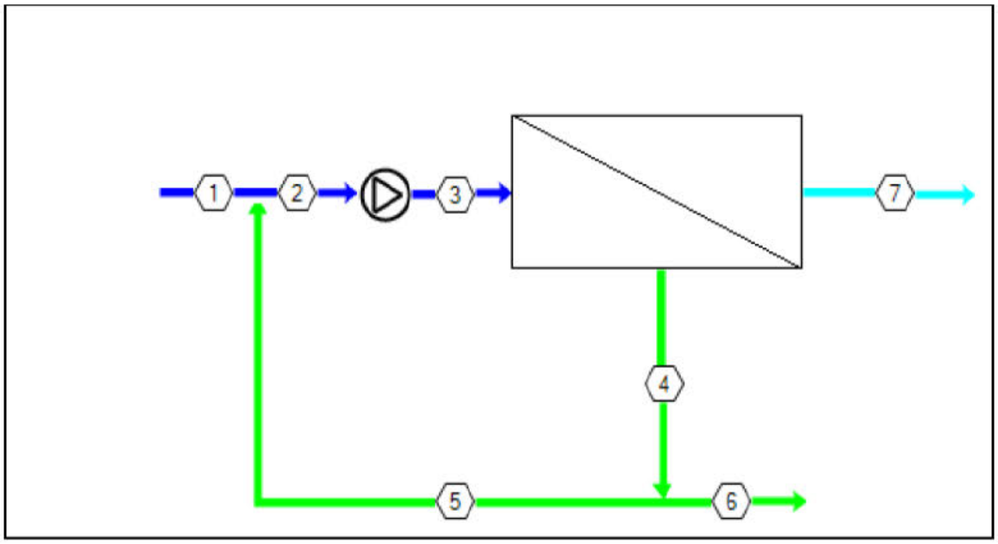
Concentrate Recirculation

Project name SWRO Desalination Page : 3/6

Temperature : 25.0 °C Element age, P1 : 0.0 years



Stream No.	Flow (m3/h)	Pressure (bar)	TDS (mg/l)	CaF2	Langelier	Ionic strength	Osmotic pressure (bar)
1	1.12	0	35564	21.2	-2.123	0.707	
2	1.17	0	36568	23.3	-2.102	0.727	
3	1.17	49.6	36568	23.3	-2.102	0.727	
4	0.720	49.3	59047	130	-1.726	1.174	
5	0.050	0	59047	130	-1.726	1.174	
6	0.670	0	59047	130	-1.726	1.174	
7	0.450	0	324	0.000	-7.628	0.006	

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Nitto HYDRANAUTICS Nitto Group Company

Concentrate Recirculation

Project name SWRO Desalination Page : 4/6

Calculated by	Randy Ncube	Permeate flow/train	0.45 m3/h
HP Pump flow	1.17 m3/h	Raw water flow/train	1.12 m3/h
Feed pressure	49.6 bar	Permeate recovery	38.46 %
Feed temperature	25.0 °C(77.0°F)	Total system recovery	40.00 %
Concentrate recirculation	0.05 m3/h	Element age	0.0 years
Feed water pH	8.10	Flux decline %, per year	5.0
Chem dose, mg/l, -	H2SO4	Fouling factor	1.00
Specific energy	5.12 kwh/m3	SP increase, per year	7.0 %
Pass NDP	14.3 bar		
Average flux rate	15.1 lmh		
		Feed type	Sea Surface MF/UF

Pass - Stage	Perm. Flow m3/h	Flow / Vessel Feed m3/h	Flow / Vessel Conc m3/h	Flux lmh	DP bar	Flux Max lmh	Beta	Stagewise Pressure Perm. bar	Stagewise Pressure Boost bar	Stagewise Pressure Conc bar	Perm. TDS mg/l	Element Type	Element Quantity	PV# x Elem#
1-1	0.4	1.2	0.7	15.1	0.3	25.1	1.06	0	0	49.3	324.5	SWC5-LD-4040	4	1 x 4M

CALCULATION OF POWER REQUIREMENT

	Pass 1	Total system power
Pump/Boost pressure, bar	49.6	
Product flow, m3/h	0.5	0.45
Pump flow, m3/h	1.2	
Pump efficiency, %	80.0	
Motor efficiency, %	90.0	
VFD efficiency, %	97.0	
Pumping power, BHP	3.1	
Pumping power, kw	2.3	2.3
Pumping energy, kwh/m3		5.12

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Nitto HYDRANAUTICS Nitto Group Company

Concentrate Recirculation

Project name	SWRO Desalination			Page : 5/6	
Calculated by	Randy Ncube		Permeate flow/train	0.45	m3/h
HP Pump flow	1.17	m3/h	Raw water flow/train	1.12	m3/h
Feed pressure	49.6	bar	Permeate recovery	38.46	%
Feed temperature	25.0	°C(77.0°F)	Total system recovery	40.00	%
Concentrate recirculation	0.05	m3/h	Element age	0.0	years
Feed water pH	8.10		Flux decline %, per year	5.0	
Chem dose, mg/l, -	H2SO4		Fouling factor	1.00	
Specific energy	5.12	kwh/m3	SP increase, per year	7.0	%
Pass NDP	14.3	bar			
Average flux rate	15.1	lmh			
			Feed type	Sea Surface MF/UF	

Pass - Stage	Perm. Flow m3/h	Flow / Vessel Feed m3/h	Flow / Vessel Conc m3/h	Flux lmh	DP bar	Flux Max lmh	Beta	Stagewise Pressure Perm. bar	Stagewise Pressure Boost bar	Stagewise Pressure Conc bar	Perm. TDS mg/l	Element Type	Element Quantity	PV# x Elem #
1-1	0.4	1.2	0.7	15.1	0.3	25.1	1.06	0	0	49.3	324.5	SWC5-LD-4040	4	1 x 4M

CALCULATION OF INVESTMENT AND WATER COST

Plant capacity as permeate	0.45 m3/h
Specific investment	22,151.11 USD/m3/h
Investment	9,968.00 USD
Plant life	15.0 years
Membrane life	5.0 years
Interest rate	4.5 %
Membrane cost	500.00 USD/element
Plant factor	90.0 %
Number of elements	4.0
Power cost	0.200 USD/kwhr
Inhibitor cost	2.20 USD/kg
Power consumption	5.12 kwhr/m3
Inhibitor dosing	3.0 mg/l
Maintenance(as % of investment)	3.0 %
Acid cost	0.15 USD/kg
Acid dosing	0.00 mg/l

CALCULATION RESULTS

Capital cost	0.17 USD/m3
Power cost	1.02 USD/m3
Chemicals cost	0.02 USD/m3
Membrane replacement costs	0.11 USD/m3
Maintenance	0.08 USD/m3
Total water cost	1.41 USD/m3

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APPENDIX 2 – ROSA Results

Reverse Osmosis System Analysis for FILMTEC™ Membranes — ROSA ROSA_Desalitech ConfigDB u399339_356
Project: SWRO Desalination Single Stage 10m3 unit 2 — Case: 1
Randy Ncube, University of KwaZulu Natal — 16/4/2020

Project Information:

Case-specific: 10 m3/d SWRO Desalination Unit

System Details

Feed Flow to Stage 1	1.13 m^3/h	Pass 1 Permeate Flow	0.45 m^3/h	Osmotic Pressure:	
Raw Water Flow to System	1.13 m^3/h	Pass 1 Recovery	40.00 %	Feed	25.22 bar
Feed Pressure	47.44 bar	Feed Temperature	25.0 C	Concentrate	42.68 bar
Flow Factor	0.90	Feed TDS	35588.35 mg/l	Average	33.95 bar
Chem. Dose	None	Number of Elements	12	Average NDP	13.19 bar
Total Active Area	31.21 M^2	Average Pass 1 Flux	14.42 lmh	Power	1.65 kW
Water Classification: Seawater with Conventional pretreatment, SDI < 5				Specific Energy	3.66 kWh/m^3

Stage	Element	#PV	#Ele	Feed Flow (m^3/h)	Feed Press (bar)	Recirc Flow (m^3/h)	Conc Flow (m^3/h)	Conc Press (bar)	Perm Flow (m^3/h)	Avg Flux (lmh)	Perm Press (bar)	Boost Press (bar)	Perm TDS (mg/l)
1	SW30-2540	2	6	1.13	47.10	0.00	0.68	46.17	0.45	14.42	0.00	0.00	633.30

Pass Streams (mg/l as Ion)					
Name	Feed	Adjusted Feed	Concentrate	Permeate	
			Stage 1	Stage 1	Total
NH4+ + NH3	0.00	0.00	0.00	0.00	0.00
K	393.00	393.00	649.25	8.62	8.62
Na	10957.00	10957.00	18111.67	224.92	224.92
Mg	1312.00	1312.00	2180.58	9.12	9.12
Ca	406.00	406.00	674.81	2.78	2.78
Sr	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00
CO3	0.00	0.00	0.00	0.00	0.00
HCO3	0.00	0.00	0.00	0.00	0.00
NO3	0.00	0.00	0.00	0.00	0.00
Cl	19751.75	19751.75	32665.20	381.47	381.47
F	1.10	1.10	1.82	0.03	0.03
SO4	2767.47	2767.47	4608.22	6.34	6.34
SiO2	0.00	0.00	0.00	0.00	0.00
Boron	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00
TDS	35588.35	35588.35	58891.57	633.30	633.30
pH	8.10	8.10	8.10	8.10	8.10

*Permeate Flux reported by ROSA is calculated based on ACTIVE membrane area. DISCLAIMER: NO WARRANTY, EXPRESSED OR IMPLIED, AND NO WARRANTY OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE, IS GIVEN. Neither FilmTec Corporation nor The Dow Chemical Company assume any obligation or liability for results obtained or damages incurred from the application of this information. Because use conditions and applicable laws may differ from one location to another and may change with time, customer is responsible for determining whether products are appropriate for customer's use. ROSA projections do not guarantee performance nor are such projections meant to be a warranty for the system or its design. If you choose to design your systems based on the ROSA projections, you will take full responsibility for such design and for the system. You acknowledge that Dow gives a system warranty only in limited circumstances and only under certain specific terms and conditions. Should you decide to buy Membranes, to the extent Dow gives its standard Membrane warranty, which is the standard FilmTec 3-year prorated element warranty, Dow will provide such a limited warranty. You acknowledge that a system warranty is not typical and is not an entitlement. You agree to use best engineering practices and process judgment in product selection and system design FilmTec Corporation and The Dow Chemical Company assume no liability, if, as a result of customer's use of the ROSA membrane design software, the customer should be sued for alleged infringement of any patent not owned or controlled by the FilmTec Corporation nor The Dow Chemical Company.

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Reverse Osmosis System Analysis for FILMTEC™ Membranes — ROSA ROSA_Desalitech ConfigDB u399339_356
Project: SWRO Desalination Single Stage 10m3 unit 2 — Case: 1
Randy Ncube, University of KwaZulu Natal — 16/4/2020

Design Warnings

-None-

Solubility Warnings

CaF2 (% Saturation) > 100%
Antiscalants may be required. Consult your antiscalant manufacturer for dosing and maximum allowable system recovery.

Stage Details

Stage 1 Element	Recovery	Perm Flow (m^3/h)	Perm TDS (mg/l)	Feed Flow (m^3/h)	Feed TDS (mg/l)	Feed Press (bar)
1	0.12	0.07	299.93	0.56	35588.35	47.10
2	0.11	0.05	419.21	0.50	40376.48	46.89
3	0.09	0.04	595.12	0.44	45105.24	46.71
4	0.07	0.03	847.64	0.40	49467.93	46.55
5	0.06	0.02	1215.24	0.37	53268.56	46.42
6	0.04	0.02	1704.85	0.35	56387.86	46.29

CHAPTER 6. Theoretical Data Analysis for a Small-Scale Reverse Osmosis Desalination Plant

Theoretical data analysis of a RO desalination plant involves the use of data extracted from the (IMSDesign) software membrane modeling software. Several relationship of parameters like feed water TDS, feed pH, feed pressure and feed temperature were plotted against permeate parameters like permeate TDS and specific energy. This article was published in the International Journal of Mechanical and Production Engineering Research and Development (IJMPERD).

Cite this article: Randy Ncube and Freddie L. Inambao, Theoretical Data Analysis for a Small-Scale Reverse Osmosis Desalination Plant, *International Journal of Mechanical and Production Engineering Research and Development.* 11(2), 2021, pp. 31-40.

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THEORETICAL DATA ANALYSIS FOR A SMALL-SCALE REVERSE OSMOSIS DESALINATION PLANT

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ABSTRACT

Reverse Osmosis (RO) has proven to be the most commonly applied technique in desalination technologies owing to its relatively low energy consumption. Ongoing research on improvement of this technology through the analysis of statistical data extracted from experiments and simulation software is being undertaken so as to maximize permeate water while at the same time using minimum energy. Analysis of experimental and theoretical data extracted from experiments and software helps to describe the performance of the RO unit and come up with satisfactory correlation models for the systems. In this article, statistical analysis of different parameters was carried out and several graphs of correlations were plotted against each other. Important RO parameters such as specific energy consumption, temperature, feed pressure and permeate total dissolved salts (TDS) were plotted against each other to come up with their graphical correlations.

KEYWORDS: Desalination, Reverse osmosis & Statistical Analysis

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Original Article

1. INTRODUCTION

All over the world potable water scarcity has always been a problem, particularly in the Middle East and Africa. Population growth and the 'improved' standard of living together with pollution and inefficient use of available water resources has added to the fresh water crisis (Kazemain et al., 2018). Water scarcity has been and will always be a problem, particularly in developing countries in Africa and the Middle East. The development of technologies that will help in the alleviation of this crisis is an ongoing process. Research and development of desalination techniques that include Reverse Osmosis (RO), Multi-Stage Flash (MSF), Vapor Compression (VC) and Multiple Effect Distillation (MED) have been carried out to supplement the supply of potable water for human, animal and plant consumption. This has led to more investment in research and development for alternative sources of potable water. Technologies such as seawater reverse osmosis (SWRO) desalination have proven beyond reasonable doubt to be the answer to this crisis. Reverse Osmosis (RO) remains the most popular technology because of high recovery rates and a relatively low permeate product TDS, accounting for 65 % of world-wide installed desalination capacity. Even though RO is the leading desalination technology, it has its own shortcomings especially when it comes to energy consumption (Kazemain et al., 2018). Robust analysis for the evaluation of alternative designs for more efficient plants is required at the feasibility stage. Optimization of the complete plant is also required (Atab et al., 2016). Table 1 summarizes several factors that need to be varied so as to potentially save on energy consumption of the system.

Table 1: Factors that affect the Energy consumption of a RO plant (Voutchkov, 2018)

Factor	Energy Saving Technlogy Trends	Potential for Energy Savings (as percentage of industry average)
Source water temperature	Use of warmer source water (collocation with power generation plants)	3 % to 5 %
Source water salinity	Use of lower-salinity source water or blend of seawater and brackish water	Over 50 %
Membrane element and system energy and productivity losses	Use of higher productivity elements. Application of lower-energy & cost RO system configurations	5 % to 15 %
High pressure RO feed pump efficiency	Maximizing pump and motor efficiency by the use of large pumps serving multiple RO trains	5 % to 10 %
Recovery of energy from RO concentrate	Use of isobaric chamber type technologies	10 % to 15 %

As technology continues to evolve, so does the RO technique. Analysis of experimental and theoretical data extracted from experiments and software helps to describe the performance of the RO unit and come up with satisfactory correlation models for the systems (Alahmad, 2010). In this study, statistical analysis was carried out to come up with several correlations (graphs) for different sets of parameters. The data used in this article was extracted from a 10 m^3 permeate water, single stage SWRO design undertaken using Hydranautics Nitto Group Company powered Integrated Membrane Solutions Design (IMSDesign) software. IMSDesign is described as a comprehensive membrane projection program that allows users to design a reverse osmosis (RO) system based on Hydranautics membranes.

2. CONCEPTUAL ANALYSIS OF DIFFERENT PARAMETERS IN AN RO DESALINATION SYSTEM

RO desalination plants consist of four main parts, namely, pre-treatment, high pressure pumps, membrane system configurations and post-treatment. SWRO desalination process performance is influenced by several factors, both directly and indirectly. These factors include concentration polarization, operating pressure, degree of fouling and scaling, specific membrane characteristics, water quality, and water temperature (Gandhidasan & Al-Mojel, 2009; Kim, Oh et al., 2009). Amongst all these factors mentioned, the performance of the whole process is significantly affected by the operating temperature. Variations of feed temperature affect performance; for example, increasing the feed temperature increases the osmotic pressure and at the same time decreases water viscosity (Kim, Oh et al., 2009). Studies show that an increase in temperature leads to an increase in permeate recovery, thereby reducing specific energy (Koutsou et al., 2020). Characteristically, the production of 1 m^3 of freshwater from seawater in a RO plant uses between 3 kWh to 10 kWh of electricity (Atab et al., 2016). Availability of fresh water depends on energy investment (Gude, 2011). Much focus on SWRO technology improvement has been on energy saving because energy accounts for most of the operating costs (Bartels & Andes, 2013). For the theoretical analysis of data reviewed in this study, the permeate recovery rate was around 40 %, feed flow and permeate flow rates varied between 1.2 m^3/h and 0.45 m^3/h respectively as shown in Table 4. Table 2 and Table 3 shows the quality and typical characteristics of the sea water used.

Table 2: Average Feed Water Temperature and Total Dissolved Solids (TDS) in milligrams/litre (mg/l) for different locations in South Africa

Location of raw water type	Feed water TDS (mg/l)	Feed water temperature (°C)
West Coast	> 35 000	9 to 14
South Coast	35 000 to 35 400	16 to 21
East Coast	34 700 to 35 400	21 to 25

Where: East Coast stretches from East London up to the Mozambican boarder, South Coast stretches from East London to Cape Agulhas and the West Coast is a region that stretches from Cape Agulhas to the mouth of the Orange river (Swartz et al., 2006)

Table 3: Main constituents of sea water off the West Coast, near Cape Town (Du Plessis et al., 2006; Swartz et al., 2006)

Total Dissolved Solids (mg/l)	35 644
Sodium (as Na mg/l)	10 957
Magnesium (as Mg mg/l)	1 312
Potassium (as K mg/l)	393
Calcium (as Ca mg/l)	406
Chloride (as Cl mg/l)	19 677
Sulphate (as SO4 mg/l)	2 757
Alkalinity (as CaCO3 mg/l)	117
Fluoride (as F mg/l)	1.1
Cyanide (as CN mg/l)	< 0.05
Dissolved Organic Carbon (mg/l)	< 1
Conductivity (µS/cm) @ 25 °C	51 000
pH (Lab)	8.1
Hardness (as CaCO3 mg/l)	6 417
CATIONS (meq/l)	614.87
ANIONS (meq/l)	614.82
Suspended Solids (mg/l) (No. 1 filter)	3.7
Suspended Solids (mg/l) (0.45 µm)	1.5
Turbidity (NTU)	6.5

Figure 1 and Table 4 show the concentrate recirculation flow diagram and different sets of parameters measured at different stages from feed to permeate stage respectively. A standard single stage RO desalination unit (Figure 1) consists of feed flow water (stages 1 and 2), passing through a high pressure pump (stage 3) and is forced through a rack of RO membrane elements in the pressure vessel(s) once to obtain permeate water (stage 7) and concentrate water (stage 4). Some of the concentrate water is recirculated (stage 5) to the feed water from the reservoir (stage 1) to recover more permeate and the process starts again. Excess concentrate water is discharged at stage 6.

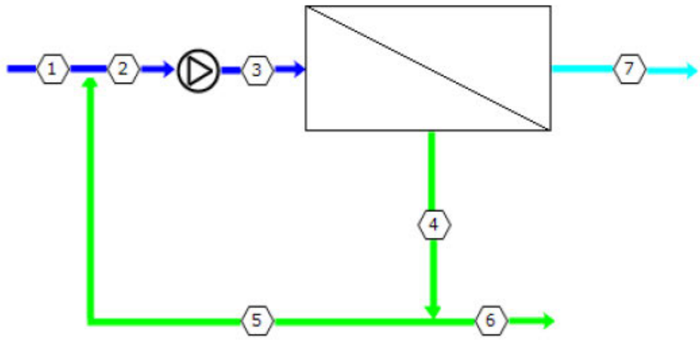

Figure 1: Schematic of a Single Stage RO with Concentrate Recirculation Flow

Table 4: Different Parameters Measured at different stages of RO Desalination

	1	2	3	4	5	6	7
Flow (m^3/h)	1.12	1.17	1.17	0.720	0.050	0.670	0.450
Pressure (bar)	0	0	49.6	49.3	0	0	0
TDS (mg/l)	35 564	36 568	36 568	59 047	59 047	59 047	324
pH	8.10	8.10	8.10	8.13	8.13	8.13	6.80
Econd (µs/cm)	55 499	56 974	56 974	89 596	89 596	89 596	704

In Table 4, the simulated results are summarized per stage, from the feed flow (stages 1 and 2) to the permeate (stage 7). Feed water is passed through a high pressure pump at 49.6 bars and a flow rate of 1.17 m^3/h (stage 3) and is forced through the RO membranes in pressure vessel(s) for desalination to take place. Concentrate water is released at a pressure of 49.3 bars (stage 4). Feed water TDS and conductivity at stage 2 slightly increases from feed water TDS at stage 1 due to the concentrate water recirculation. Stages 4, 5 and 6 represent the concentrate water characteristics. A high concentrate water TDS and conductivity is recorded in these stages because desalination has taken place. In stage 7, permeate TDS and conductivity is 324 mg/l and 704 µs/cm as per design requirements.

2.1. The Effects of Feed Temperature on Specific Energy

Operation temperature is one of the most significant factors that affects the RO process. Temperature varies inversely proportionally to water viscosity. As temperature increases viscosity decreases, leading to RO membranes becoming more permeable. Specific energy is defined as the amount of energy required to produce a unit of potable water (Bartels & Andes, 2013). An increase in temperature subsequently leads to reduced power consumption and hence specific energy consumption. This in turn leads to increased productivity at lower production costs and consequently, economic gains (Nisan et al., 2005). The effects of temperature change on the efficiency of the system, especially on energy, for temperature ranges of between 15 °C to 40 °C leads to a decrease in water viscosity, resulting in an increase in membrane permeability. A change of a degree in temperature results in a variation of approximately 3 % change in permeability flux (Koutsou et al., 2020). The effects of temperature on the specific energy of the system is analysed in Figure 2.

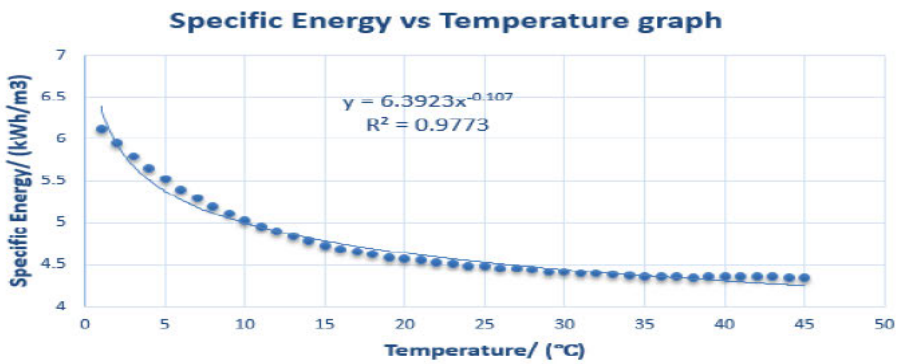

Figure 2. Evolution of Specific Energy as a Function of Feed Temperatures

2.2. The Effects of Feed Temperature on Permeate Total Dissolved Solids (TDS)

Temperature variations lead to several changes in the functioning of the RO technology. An increase in feed temperature decreases the viscosity of the feed water. A decrease in viscosity leads to the RO membrane becoming more permeable. Accordingly, actual operations with a higher temperature condition may lead to a rise in both the permeate TDS and permeate flow rate (Kim, Oh et al., 2009; Salahi et al., 2010). Salinity and temperature variations for a given pressure influence the physiochemical properties of water (Koutsou et al., 2020). Thus, optimization of operating temperature control is needed to improve the SWRO desalination process efficiency (Kim, Oh et al., 2009). Figure 3 shows the analysis of the effects of feed temperature on the permeate TDS of the system.

2.3. The Effects of Temperature on Feed Pressure

Approximately 75 % of the total running cost of an RO plant is related to high pressure pumps (Gude, 2011). The efficiency of these high pressure pumps is of paramount importance. A seawater RO desalination process generally uses high pressure centrifugal feed pumps (Koutsou et al., 2020). The required feed pressure depends on the following factors: the design permeate flux, feed water osmotic pressure (feed salinity), and the temperature of the feed water (Wilf & Klinko, 2001). Figure 4 shows the relationship between feed pressure and temperature.

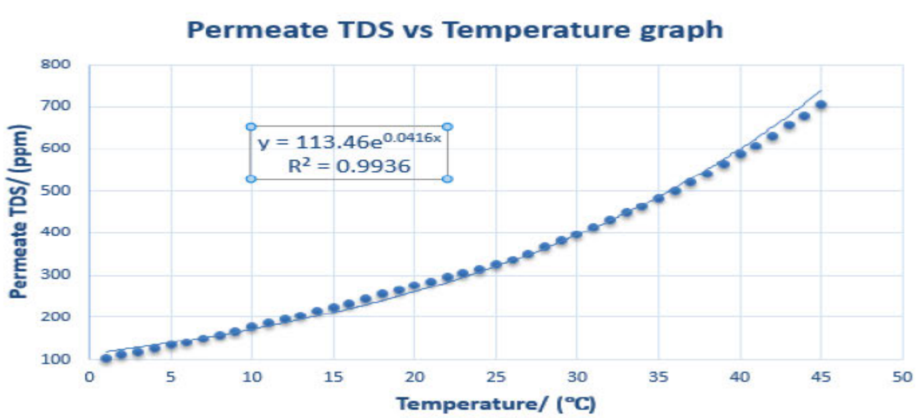

Figure 3. The Relationship of Temperature and Permeate TDS

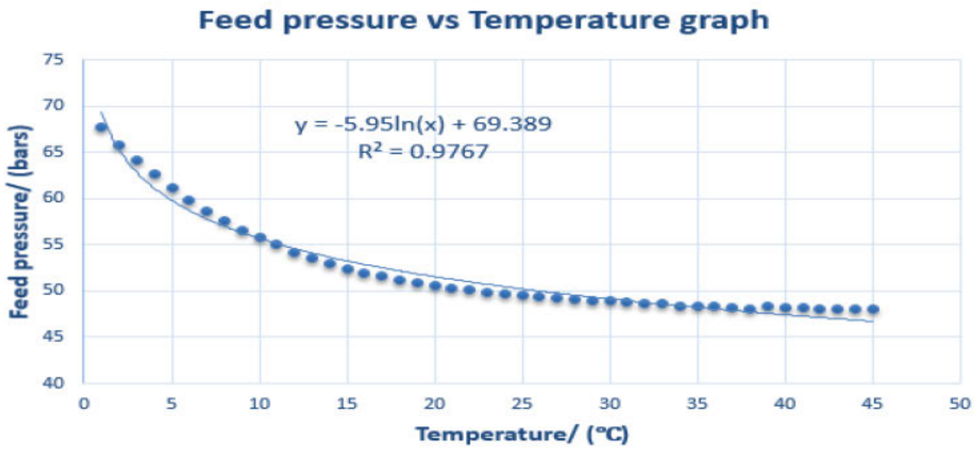

Figure 4: The Feed Pressure vs Temperature Correlation

2.4. The Effects of Pressure on Specific Energy

Previous research indicates that temperature and operating pressure can be used in the performance improvement process as controllable factors. The net driving pressure, influenced by the operating pressure, can control and determine permeate flow rate (Kim, Lee et al., 2009). There is an almost linear direct proportionality between feed pressure and energy consumption of the RO plant as well as permeate production (Gandhidasan & Al-MOjel, 2009). To overcome the osmotic pressure of the saline feed water, a relatively high hydraulic pressure is necessary. This therefore implies that when pressurizing the feed flow, a high consumption of energy is required. Generally, an increase in applied pressure yields an increase in the flux of feed water (Atab et al., 2016; Guler et al. 2009). The energy required to drive a RO plant is directly proportional to feed pressure (Wilf & Klinko, 2001). Figure 5 shows the relationship between feed pressure and specific energy, clearly indicating the effects of feed pressure on the specific energy of the system.

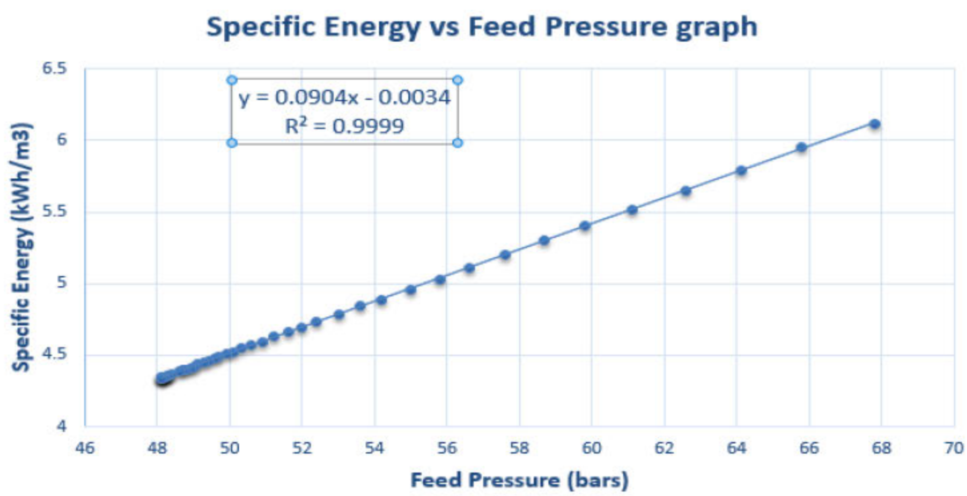

Figure 5. The Specific Energy vs feed Pressure Graph

2.5. The Effects of permeate TDS on Specific Energy

The required feed pressures for desalination for brackish water are in the range of 10 bars while for seawater they may be as high as 75 bars (Laborde et al. 2001). As feed pressure increases the solute concentration gradually decreases, indicating that less permeate TDS is produced (Atab et al., 2016; Gandhidasan & Al-MOjel, 2009). There is an exponential decrease in permeate TDS when feed pressure is increased from around 50 bars to around 70 bars as shown in Figure 6. For optimum operation, RO units require automatic pressure adjustments and controls (Laborde et al. 2001).

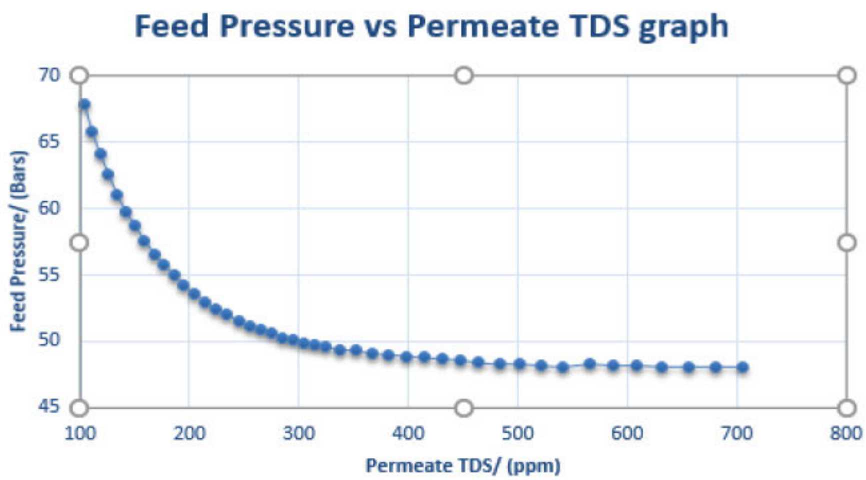

Figure 6. The Feed Pressure vs permeate TDS Graph

3. RESULTS AND DISCUSSIONS OF THE RO SYSTEM

In the current study, the development of the correlations started with the computer simulations for the RO system, using conceptual design carried out by the IMSDesign membrane modeling software. In this setup, four elements of SWC5-LD-4040 Hydranautics SWC composite polyamide membranes were selected. These elements have high salt rejection and maximum allowable pressure.

Water characteristics in Table 3 were used as inputs into the software. According to Stillwell and Webber (2016), the statistical evaluation of the small scale RO specific energy consumption (SEC) is given by Eq. 1:

$$SEC = 7.7 + 3.9 * 10^{-2} q_{rw} - 8.6 * 10^{-2} q_{rw} + \frac{1.7}{1-R} + 6.2 * 10^{-4} c_{rw} + 4.2 * 10^{-3} c_{pw} - 0.34P - 5.4ER - 0.2T \quad \text{Eq. 1}$$

Where: SEC represents the estimated specific energy consumption (kWh/m^3), q_{rw} is raw water flow rate (m^3/day), q_{pw} is product water flow rate (m^3/day), R is recovery, c_{rw} is raw water TDS (mg/l), c_{pw} is product water TDS (mg/l), P is pressure (bar), ER represents the use of energy recovery systems, and T is temperature (°C).

The graphs above show the effects of varying certain inputs to affect the outcome. Figure 2 shows a trend where an increase in temperature shows a decrease in specific energy consumed. At temperatures of more than 30 °C the graph shows that there is a minimum or no change at all in specific energy. In Figure 3, the relationship between temperature and permeate TDS shows that as temperature increases, the permeate TDS also increases. For temperatures between 20 °C and

35 °C the permeate TDS is found to be between 300 ppm and 500 ppm, which is the desired range for this setup. It can also be seen that feed pressure increases as temperature decreases as shown in Figure 4. There is a sharp increase in feed pressure as temperature decreases from 20 °C to 5 °C. The feed pressure remains constant or shows insignificant change from temperatures greater than 25 °C. Figure 5 and Figure 6 show the effects that permeate TDS have on specific energy and feed pressure respectively. It can be deduced from the two graphs that for low permeate TDS, high specific energy and feed pressure is required. To achieve the 500 ppm permeate TDS required by the WHO guidelines for potable water, about 4.4 kWh/m^3 specific energy and about 48.5 bars of feed pressure is required. For a constant feed flow rate, specific energy increases as feed pressure increases. This is shown in the graph of specific energy vs feed pressure in Figure 4. The relationship shows a near linear positive proportionality.

4. CONCLUSIONS

Factors such as feed water flow rate, temperature, salinity, and membrane type, are very important in the monitoring and controlling of the RO system so as to achieve optimal performance. It is noted that energy efficiency can be improved by variation of feed temperature, that is to say, an increase in feed water temperature results in the reduction of specific energy consumption. It can also be deduced that the specific energy increases as feed pressure increases, and the relationship between temperature and permeate TDS shows that as temperature increases, the permeate TDS also increases. Therefore, to promote the adoption of a more sustainable, cost-effective, and environmentally friendly desalination operation, parameters such as temperature and feed flow rate should be optimized over other parameters.

REFERENCES

1. *Alahmad, M. (2010). Prediction of performance of sea water reverse osmosis units. Desalination, **261**(1-2), pp. 131-137. DOI: https://doi.org/10.1016/j.desal.2010.05.018.*
2. *Atab, M. S., Smallbone, A. & Roskilly, A. (2016). An operational and economic study of a reverse osmosis desalination system for potable water and land irrigation. Desalination, **397**, pp. 174-184. DOI: https://doi.org/10.1016/j.desal.2016.06.020.*
3. *Bartels, C. R. & Andes, K. (2013). Consideration of energy savings in SWRO. Desalination and Water Treatment, **51**(4-6), pp. 717-725. DOI: https://doi.org/10.1080/19443994.2012.700038.*
4. *Du Plessis, J., Burger, A., Swartz, C., & Musee, N. (2006). A desalination guide for South African municipal engineers. Pretoria: Water Research Commission. Available: http://www.coastkzn.co.za/wp-content/uploads/2019/02/desalination-Guideline-for-ENGINEERS-WRC.pdf.*
5. *Gandhidasan, P. & Al-Mojel, S. A. (2009). Effect of feed pressure on the performance of the photovoltaic powered reverse osmosis seawater desalination system. Renewable Energy, **34**(12), pp. 2824-2830. DOI: https://doi.org/10.1016/j.renene.2009.04.029.*
6. *Gude, V. G. (2011). Energy consumption and recovery in reverse osmosis. Desalination and Water Treatment, **36**(1-3), pp. 239-260. DOI: https://doi.org/10.5004/dwt.2011.2534.*
7. *Guler, E., Piekacz, J., Ozakdag, D., Kujawski, W., Arda, M., Yuksel, M., & Kabay, N. (2009). Influence of the chosen process parameters on the efficiency of seawater desalination: SWRO pilot plant results at Urla Bay seashore. Desalination and Water Treatment, **5**(1-3), pp. 167-171. DOI: https://doi.org/10.5004/dwt.2009.586.*
8. *Kazemain, M., Ebrahimi-Nejad, S., Jaafarian, M. (2018). Experimental investigation of energy consumption and performance of reverse osmosis desalination using design of experiments method. International Journal of Engineering, **31**(1), pp. 79-87. Available: http://www.ije.ir/article_73095.html*

9. *Kim, S. J., Oh, S., Lee, Y. G., Jeon, M. G., Kim, I. S., & Kim, J. H. (2009). A control methodology for the feed water temperature to optimize SWRO desalination process using genetic programming. Desalination,* ***247****(1-3), pp. 190-199. DOI: https://doi.org/10.1016/j.desal.2008.12.024.*

10. *Kim, S. J., Lee, Y. G., Oh, S., Lee, Y. S., Kim, Y. M., Jeon, M. G., Lee, S., Kim, I. S., & Kim, J. H. (2009). Energy saving methodology for the SWRO desalination process: control of operating temperature and pressure. Desalination,* ***247****(1-3), pp. 260-270. DOI: https://doi.org/10.1016/j.desal.2008.12.006.*

11. *Koutsou, C., Kritikos, E., Karabelas, A., & Kostoglou, M. (2020). Analysis of temperature effects on the specific energy consumption in reverse osmosis desalination processes. Desalination,* ***476****, pp. 114213. DOI: https://doi.org/10.1016/j.desal.2019.114213.*

12. *Laborde, H., Franca, K., Neff, H., & Lima, A. (2001). Optimization strategy for a small-scale reverse osmosis water desalination system based on solar energy. Desalination,* ***133****(1), pp. 1-12. DOI: https://doi.org/10.1016/S0011-9164(01)00078-9.*

13. *Nisan, S., Commercon, B., & Dardour, S. (2005). A new method for the treatment of the reverse osmosis process, with preheating of the feedwater. Desalination,* ***182****(1-3), pp. 483-495. DOI: https://doi.org/10.1016/j.desal.2005.02.041.*

14. *Salahi, A., Mohammadi, T., Rekabdar, F., & Mahdavi, H. (2010). Reverse osmosis of refinery oily wastewater effluents. Available: https://www.sid.ir/en/Journal/ViewPaper.aspx?ID=204554.*

15. *Stillwell, A. S. & Webber, M. E. (2016). Predicting the specific energy consumption of reverse osmosis desalination. Water,* ***8****(12), pp. 601. DOI: https://doi.org/10.3390/w8120601.*

16. *Swartz, C., Du Plessis, J., Burger, A., & Offringa, G. (2006). A desalination guide for South African municipal engineers. Water SA,* ***32****(5). DOI: 10.4314/wsa.v32i5.47845.*

17. *Voutchkov, N. (2018). Energy use for membrane seawater desalination–current status and trends. Desalination,* ***431****, pp. 2-14. DOI: https://doi.org/10.1016/j.desal.2017.10.033.*

18. *Wilf, M. & Klinko, K. (2001). Optimization of seawater RO systems design. Desalination,* ***138****(1-3), pp. 299-306. DOI: https://doi.org/10.1016/S0011-9164(01)00278-8.*

CHAPTER 7. Experimental Data Analysis for a Reverse Osmosis Desalination Plant

Experimental data analysis of a RO desalination plant involves the use of data extracted from the Victoria and Alfred (V & A) desalination plant located in Cape Town, South Africa. The data was collected and statistically analyzed using Microsoft Excel and different relationships of parameters like feed and permeate total dissolved salts (TDS), temperature, pressure, energy and pH were plotted. This article was published in the International Journal of Mechanical and Production Engineering Research and Development (IJMPERD).

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EXPERIMENTAL DATA ANALYSIS FOR A REVERSE OSMOSIS DESALINATION PLANT

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ABSTRACT

Water scarcity is slowly becoming a threat to the normal livelihoods of people as the human population continues to increase. Affordable options of sourcing potable water are needed, especially in Africa where purification of water is generally expensive. Reverse osmosis (RO) desalination has proven to be one of the most preferred and applied techniques in the desalination of water due to its production of good permeate water quality at low cost compared to other desalination techniques. Research and development for the design and optimization of this process to come up with optimum design parameters has been ongoing. This article summarizes the data extracted from experiments done on one of the major desalination plants in Cape Town, South Africa. The data was collected and statistically analyzed using Microsoft Excel and different relationships of parameters like feed and permeate total dissolved salts (TDS), temperature, pressure, energy and pH were plotted.

KEYWORDS: Desalination, Reverse Osmosis & Experimental Data Analysis

Original Article

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1. INTRODUCTION

According to WHO guidelines, humans need drinking water with less than 500 mg/l of salt [1]. With the shortage of clean and drinkable water and the abundance of seawater, a process known as desalination has been employed. Desalination, sometimes known as desalting, is defined as the process of removing salts from water in order to produce potable water [2]. Recent studies have shown that reverse osmosis (RO) has, and is still proving to be, the most efficient desalination technique for brackish water and seawater [1]. Efficient as it is, it still has several issues that need to be addressed to improve its operations. Some of the design parameters like membrane fouling, osmotic pressure, specific energy and permeate water quality produced need to be improved in order to optimize desalination plants [3]. Some of these input and output parameters were studied based on experimentation in a seawater desalination plant located along the Atlantic Ocean coastal city of Cape Town, South Africa. Parameters like feed and permeate total dissolved salts (TDS), pressure, temperature, pH, energy consumption and conductivity were measured and compared against each other in the month of November 2018, and several relationships and correlations were plotted.

2. DESIGN PARAMETERS

The design of a sea water reverse osmosis (SWRO) plant involves several parameters that need to be studied so as to optimize the desalination process. Parameters such as feed water temperature, pressure, pH and TDS need to be considered before the operation takes place. Some of the important parameters to be considered for optimization are described in the subsections below.

2.1 Feed Water Quality

Feed water quality is one of the main factors affecting the process of desalination and determining the water quality to be treated. Feed water quality provides an overview of water characteristics such as the feed TDS, pH, amount of magnesium, chloride, sulphates and fluoride ions present in the water before treatment. Feed water temperature is also one of the paramount parameters to consider as this affects the performance of the membranes and also the quality of permeate water produced.

2.1.1 Feed Water Salinity

An increase in feed water TDS has a negative effect on the performance of the RO desalination plant. This increase normally results in a decrease in membrane flux [4]. Feed water containing a high salt concentration has a high osmotic pressure, therefore higher hydraulic pressure is required to produce fresh potable water from feed water with high salinity [5]. In general, low feed TDS tends to produce a higher recovery ratio compared to a higher feed TDS [6].

2.1.2 Permeate Water

Permeate water is the desalted water produced after the desalination process. Sea water reverse osmosis plants that produce low permeate TDS quality also tend to consume more energy. This is so because permeate water quality is directly proportional to the energy required during desalination [5].

2.1.3 Feed Water pH

The hydrogen ion concentration is important in defining the alkalinity equilibrium of ions. pH shows slight effects on permeate TDS but nonetheless, it is inversely proportional to permeate TDS. Higher pH results in lower permeate salt concentration, which is a desired effect [7].

2.2 Pre-Treatment

Pre-treatment is the process of removing all suspended solids in the feed water so that membranes do not undergo easy degradation through microbial growth or salt precipitation. Proper pre-treatment is one of the key factors in maintaining successful long term RO performance and prolonging the lifespan of the membranes [8, 9]. If larger and more visible particles are not removed from the feed water they will naturally clog the feed flow channels in the membrane. Such fouling is prevented by reducing feed water turbidities and the Silt Density Index (SDI) to less than 1 NTUT and 4.0 respectively through a 0.45 micron filter. The potential of colloidal fouling is not detected by turbidity and SDI. Anti-scalants are used to control scaling through binding to nascent seed crystals, at the same time preventing them from growing into scales, safely ejecting them with the reject water [10]. The applied pre-treatments can help in prolonging the life span of RO membranes, increasing the membrane's performance, producing a higher quality of product water, and minimizing the frequency of chemical cleaning. Non-conventional pre-treatment routines like nanostructured pre-treatment membranes improve the operational cost by reducing the need for adding chemical additives to the feed water and reduce the operational maintenance of the desalination system [10, 11]. Pre-treatment reduces the amount of energy required to produce permeate water [12, 13]. Pre-treatment methods such as ultrafiltration (UF) and micro filtration (MF) are regarded as the best pre-treatment methods for RO [14].

2.3 RO Membranes

Recently, research has focused on spiral wound membranes in the development of membranes that provide greater filtration surface, an increase in productivity, and high salt rejection [15]. Polymeric membranes have dominated commercial applications of RO since the very first desalination plant. Owing to their technological development, they offer ease of handling, improved performance and low-cost fabrication in permeability and selectivity. Thin film composite (TFC) polyamide RO dominates the membrane market. These membranes consist of three layers: a structural support layer made of polyester web (120 µm to 150 µm thick), an ultra-thin (about 0.2 µm) barrier layer on the upper surface and a microporous interlayer of about 40 µm on the surface [16]. Studies have shown that usage of high permeability membranes during the desalination process has the potential to reduce RO costs [17]. Fig. 1 shows the RO spiral wound membrane configuration.

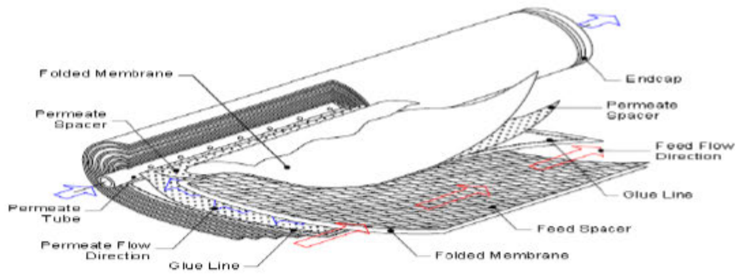


Figure 1: Spiral Wound RO Membrane Module Configuration [18].

3. MODELING AND MODEL VALIDATION OF THE PLANT

Modeling of the plant is done so as to come up with mathematical relationships between the different variables. Below are the selected equations for the modeling of a SWRO desalination unit. Permeate flow rate, Q_w, can be calculated using Eq. 1:

$$Q_w = A(\Delta P - \Delta\pi) \qquad Eq. 1$$

Where ΔP is feed and permeate pressure difference and Δπ is osmotic pressure [19].

The recovery ratio, K, is given by Eq. 2:

$$K = \frac{Q_p}{Q_f} \qquad Eq. 2$$

Where Q_p is permeate flow and Q_f is feed flow. The recovery ratio tends to decrease with an increase in feed TDS at a given temperature [20].The temperature correlation factor (TCF) for a given RO plant is calculated by Eq. 3:

$$TCF = e^{\left[\frac{E_m}{R}\left(\frac{1}{273+T} - \frac{1}{298}\right)\right]} \qquad Eq. 3$$

Where E_m is membrane activation energy, R is gas constant and T is temperature [21].

The theoretical calculations of specific energy consumption (SEC) and permeate flux (J_v) are given by Eq. 4 and Eq. 5 respectively [22]:

$$SEC = \frac{E_{bp} + E_{hp} + E_{sp}}{Q_p} \qquad Eq. 4$$

$$J_v = \frac{Q_p}{A} \qquad Eq.5$$

Where: E_{bp}, E_{hp} and E_{sp} are energies consumed by the booster pump, high pressure pump and supply pump respectively, and Q_p and A represent the permeate water flow rate and area of membrane respectively. Salt rejection, R_s, and total mass balance, Q_fC_f are calculated respectively by Eq. 6 and Eq. 7:

$$R_s = 1 - \frac{TDS_p}{TDS_f} \qquad Eq.6$$

$$Q_fC_f = Q_pC_p - Q_rC_r \qquad Eq.7$$

Where C_f, C_p and C_r are feed, permeate and reject salts mass concentrations respectively, and Q_r is reject water flow rate [23].

Normalized Temperature, TMP*:

$$TMP^* = TCF * TMP \qquad Eq.8$$

Temperature Correction Factor, (TCF) which is a factor that takes into cognisance the effect of the temperature. Different TMP values can be compared to each other at different temperatures and transported to the same of 25 °C (reference temperature) [24].

4. EXPERIMENTAL DATA

The experiments were conducted on the Victoria and Alfred (V&A) Waterfront desalination unit in Cape Town, South Africa in the month of November, 2018. Figure 2 and Figure 3 show the aerial and side view of the plant respectively.

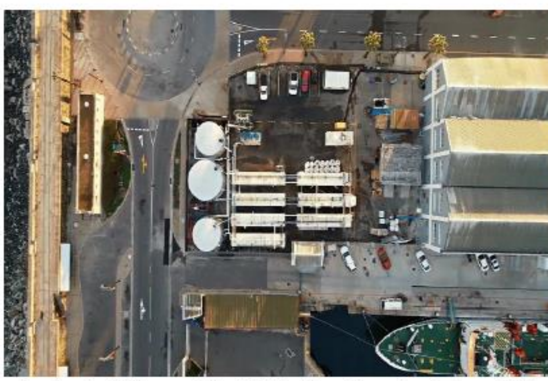


Figure 2: Aerial View of the V&A Desalination Plant [25]. Figure 3: Side View of the Desalination Plant [25].

The plant is a fully containerised 2MLD SWRO desalination plant. Figure 4 shows the schematic diagram of the plant.

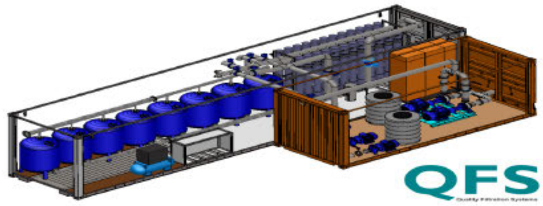


Figure 4: Schematic Diagram of the Plant [25].

The plant consists of 3 main trains, namely 500-3, 500-4 and 1000-10. Each train is different. The following section is dedicated to the description of the trains.

4.1 The 500-3 Desalination Train

The 500-3 train consists of 6 pressure vessels, each housing 7 membranes, making a total of 42 membranes. The membranes are 8 inch LG-SW-440 SR membranes, with a surface area of 41 m^2. Table 1 shows the summary of the characteristics of the membrane used. Feed water is pumped through the media and cartridge filter by a low pressure pump. After filtration, the saline water is pumped into the vessels by a high pressure pump. Permeate water is collected. Brine energy recovery is done with a pressure exchanger (ERI PX55). The mass balance for the feed flow (not directly measured) is exactly equal to the permeate flow. The remainder of the feed flow (which makes up for the volume lost in brine) is "pumped" to the feed by the pressure exchanger. Figure 5 shows the schematic diagram of the train.

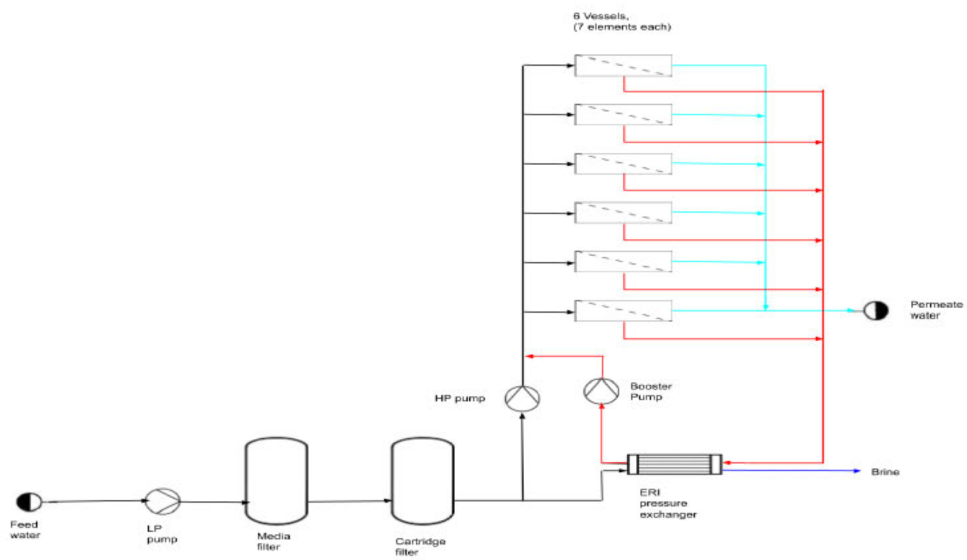


Figure 5: Schematic Diagram for the 500-3 Train.

Table 1: LG-SW-440 SR Membrane Specifications

Membrane element	LG-SW440 SR
No. of vessels	6
No. of membranes in each vessel	7
Total no. of membranes	42
Max. operating temperature/ (°C)	45
Max. operating pressure/ (bars)	82.7
Max. feed flow/ (m^3/h)	18
Salt rejection/ (%)	99.85
pH range	2 to 11
Membrane area/ (m^3)	41
Membrane configuration	Spiral wound
Membrane polymer	Thin-film nanocomposite polyamide

4.2 The 500-4 Desalination Train

The 500-4 train consists of 7 pressure vessels, each housing 6 membranes, making a total of 42 membranes for the train. The membranes are 8 inch, hydranautics SWC-5, not LD, with a surface area of 41 m^2. Table 2 summarises the characteristics of the membrane used in this train. Feed water is pumped through the media and cartridge filter by a low pressure pump at a pressure of around 3 bars. Filtered water is pumped at about 40 bar into the vessels for desalination by a horizontal multistage centrifugal high pressure pump. Brine energy is recovered with a turbo energy recovery system. The brine flow powers the turbine, and the turbine shaft turns a pump, which boosts the pressure from the feed pump from about 40 bars to operating feed pressure of about 55 bars. This specific modular equipment (skid) has no pressure on the brine, only feed pressure. Permeate pressure can be assumed to be at 0.3 bar (static and negligible friction loss). Figure. 6 shows the schematic diagram for the 500-4 train.

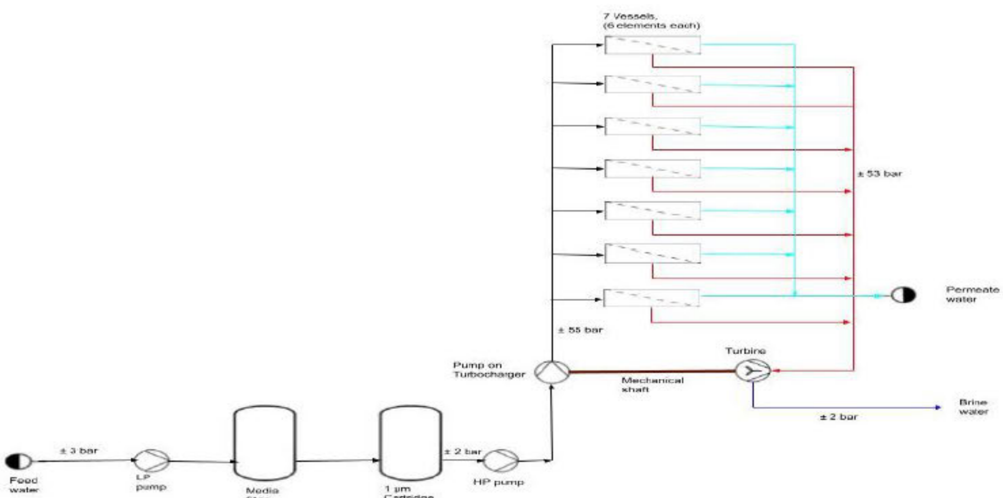


Figure 6: The Schematic Diagram of the 500-4 Train.

Table 2: SWC-5 Membrane Specifications

Membrane element	SWC-5
No. of vessels	7
No. of membranes in each vessel	6
Total no. of membranes	42
Max. operating temperature/ (°C)	45
Max. operating pressure/ (bars)	82.7
Max. feed flow/ (m^3/h)	17
Salt rejection/ (%)	99.8
pH range	2 to 11
Membrane area/ (m^3)	41
Membrane configuration	Spiral wound
Membrane polymer	Composite polyamide

4.3 The 1000-10 Desalination Train

The 1000-10 train is similar to the 500-4 in that it has a turbo charged and multistage feed pump. All operating conditions are similar to the 500-4 train. Figure 7 shows the schematic diagram of the 1000-10 train. The only difference is that 1000-10 has 6 pressure vessels, each holding 7 membranes, making a total of 42 membranes. This is also an internally staged design, which means that the lead membrane in each vessel (on the side of the feed) are DOW SW30XLE-440i, and the remaining 6 are DOW SW30-ULE-440i. Table 3 and 4 are summaries of the membranes used in this train.

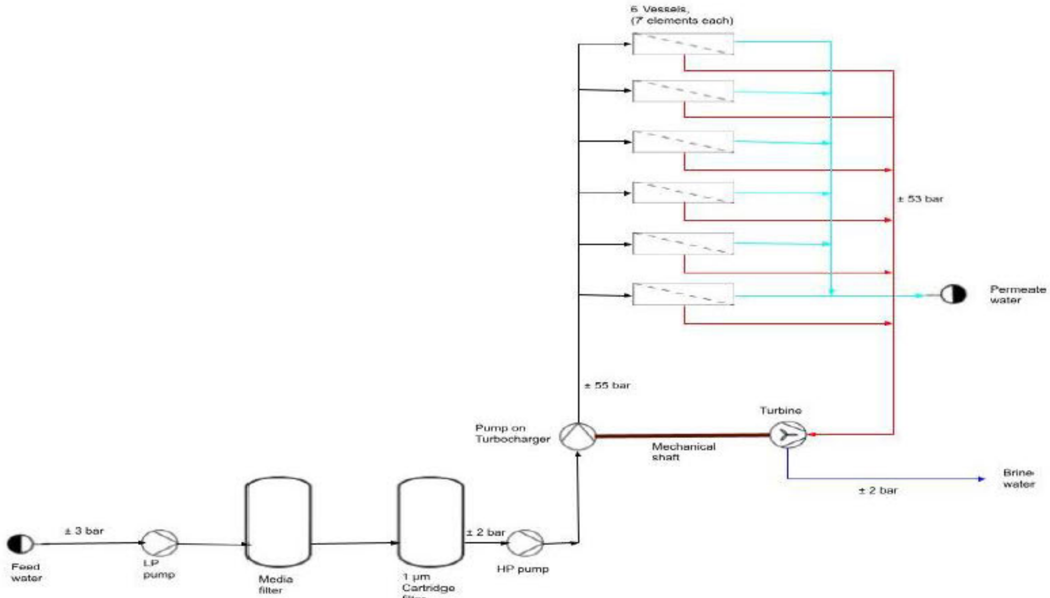


Figure 7: Schematic Diagram of the 1000-10 Train.

Table 3: DOW SW30XLE-440i Membrane Specifications

Membrane Element	DOW SW30XLE-440i
No. of vessels	6
No. of membranes in each vessel	1
Total no. of membranes	6
Max. operating temperature/ (°C)	45
Max. operating pressure/ (bars)	83
Salt rejection/ (%)	99.8
pH range	2 to 11
Membrane area/ (m^3)	41
Membrane polymer	Polyamide Thin-Film Composite

Table 4: DOW SW30-ULE-440i Membrane Specifications

Membrane Element	DOW SW30-ULE-440i
No. of vessels	6
No. of membranes in each vessel	6
Total no. of membranes	36
Max. operating temperature/ (°C)	45
Max. operating pressure/ (bars)	83
Salt rejection/ (%)	99.7
pH range	2 - 11
Membrane area/ (m^3)	41

The average monthly parameters are recorded below:

Recovery	- 31 %	Average feed TDS	- 32800 mg/l
$Q_{permeate}$	- 1367 m^3/d	Average permeate TDS	- 490 mg/l
Q_{feed}	- 4446 m^3/d	Average feed temperature	- 16 °C
Q_{brine}	- 3079 m^3/d	Average feed pH	- 7.2
		Average feed pressure	- 55 bar

5. RESULTS

The scope of this thesis will look at the effects of feed TDS, pH, pressure and temperature on the performance of RO desalination system. The table below shows the operating conditions of the plant with different parameters like feed temperature, pH and feed TDS varied according to the lab test results of feed water during the experimentation and data extraction process. The experiments were done separately in the month of November 2018 and the following data was recorded. The average feed and permeate TDS for the plant were 32800 ml/l and 490 mg/l. Table 5 shows a summary of operating parameters and averages for the plant. Table 6 shows the flows measured at different points of operation, and the feed, permeate and brine flow rates. It also shows that the plant was operating at 31 % recovery.

Table 5 A Summary of the Average Daily Parameters for the Operation of RO Desalination Plant

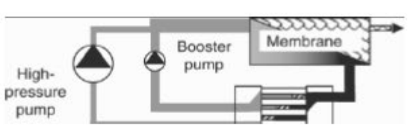
Quality						
Quality Parameters for the Day						
Measurement		Minimum	Maximum	Average	Spec	Unit
Final Water						
Conductivity		618.0	877.0	720.5		*µS/cm*
TDS		395	561	461		*mg/l*
pH		7.4	9.2	8.5		
Turbidity		0.1	0.7	0.4		*NTU*
Disinfectant residuals (Cl_2)		0.9	1.0	0.9		*mg/l*

E. coli							*cfu/1ml*
Heterotrophic Plate count							*cfu/100ml*
Treatment chemicals (soda Ash)							*kg*
Treatment chemicals (calcium chloride)							*kg*
Raw Water							
Conductivity			50.1	52.4	51.1		*mS/cm*
TDS			32064	33536	32704		*mg/l*
pH			6.3	7.8	7.2		
Turbidity			1.5	4.6	2.9		*NTU*
Temperature			12.2	17.0	13.3		*deg C*
Brine/Waste Discharge							
Salinity			69.3	74.3	71.4		*mS/cm*
TDS			44352	47552	45696		*mg/l*
pH			6.2	7.7	6.7		
Temperature			12.2	14.6	13.4		℃
Dissolved Oxygen							*ppm*
TSS							
Turbidity			0.5	2.4	1.2		*NTU*

Table 6: Recorded Flow Meter Values for Feed, Permeate and Brine Flows and Plant Recovery

Process volumes					
Daily Accumulated Flow for the Day					
Flow meter	**Start**	**End**	**Actual Throughput**	**Target Through-put**	**Unit**
Raw Water Feed	506482.0	510928.0	4446.0		m^3/day
Final Product Discharge	103217.0	104584.0	1367.0		m^3/day
Final Waste Discharge	[redacted]		3079.0		m^3/day
Water distribution network					m^3/day
Plant water recovery			31%		%

Feed water, at an average temperature of 16 °C, is pumped into the trains by a pressure pump at an average pressure of 55 bars. The actual feed flow rate of the plant is 4 446 m^3/d at an average feed flow of 240 m^3/h. At a plant recovery rate of 31 %, the permeate flow rate is 1 367 m^3/d as compared to the design specification of 2 000 m^3/d. To boost the feed pressure and recover energy for the plant, an energy recovery unit is used. The plant uses an ERI pressure exchanger. A pressure exchanger is a rotary energy device comprising two end caps, a sleeve and a rotating rotor [26]. The general schematic diagram of the ERI pressure exchanger is shown in Figure. 8.



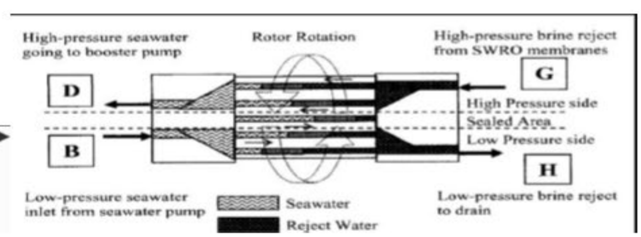


Figure 8: Schematic Diagram of an ERI Pressure Exchanger [27].
Figure 9: Pressure Exchanger Working Principle [26].

The pressure exchanger working principle is summarized in Fig. 9. Pressure is transmitted through a short period of contact time. The main principle is to transmit pressure from high pressure reject water to the low pressure feed [26].

5.1 Effects of pH on Permeate TDS and Conductivity

Feed pH was recorded every time before the operation proceeded. The average pH for the experimental period of operation and experimentation was 7.75. The average experimental day values of pH and permeate TDS are plotted in the bar graph in Figure 10.

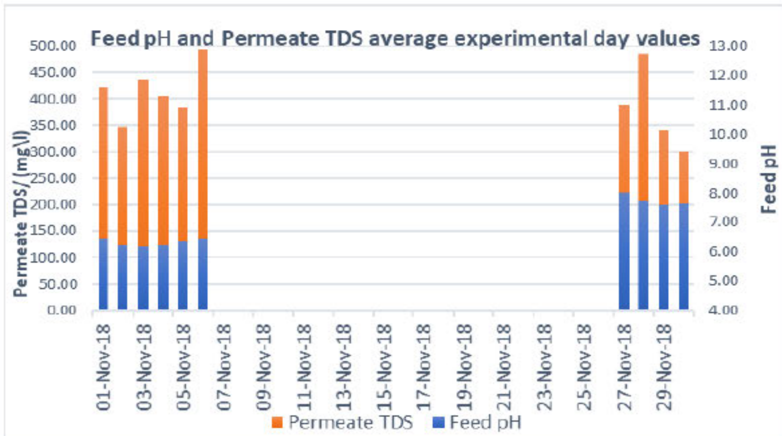
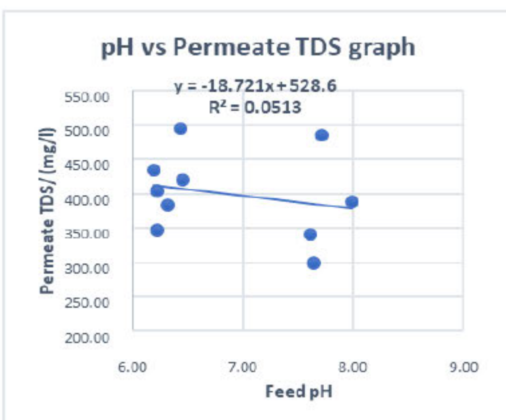


Figure 10: Average Permeate TDS and Feed pH Values on Experimental Days.

The feed pH and permeate TDS graph is plotted in Figure 11. The effects of feed pH on permeate conductivity on the month of November 2018 is plotted in Figure 12. These graphs clearly show a general decrease in permeate TDS and conductivity as feed pH increases.



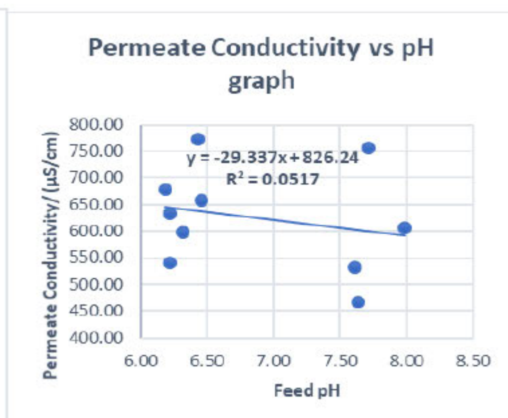


Figure 11: Permeate TDS as a Function of Feed pH Figure 12: Permeate Conductivity as a Function of Feed pH

5.2 The Effects of Feed TDS on Permeate TDS

Feed TDS has a major effect on the quality of water produced [28]. Permeate TDS tends to systematically increase as feed TDS increases [20]. Feed TDS was recorded before being pressurised in the plant for the whole period of operation. The average daily values for feed and permeate TDS are plotted in the bar graph in Figure. 13.

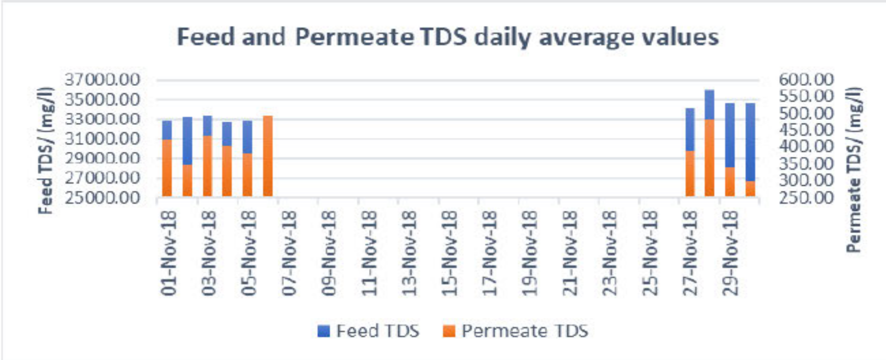


Figure 13: Average Daily Values for Feed and Permeate TDS.

The effects of feed TDS on permeate TDS at constant temperature is plotted in the graph in Figure. 14.

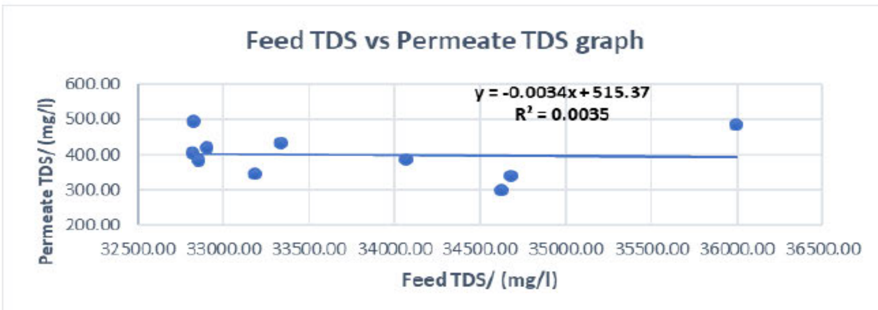


Figure 14: The Relationship between Feed and Permeate TDS.

5.3 The Effects of Feed Temperature

Feed water temperature change has several effects on the desalination process. Recent research has found that both the product concentration and flow rate increases with an increase in temperature and this results in an increase in recovery, and subsequent increase in the mechanical power consumption [21]. According to Guler (2019), a decrease in temperature reduces the conductivity and turbidity but increases the mineral rejection of the permeate water [29]. Figure 15 shows the average experimental day values of feed temperature and permeate TDS.

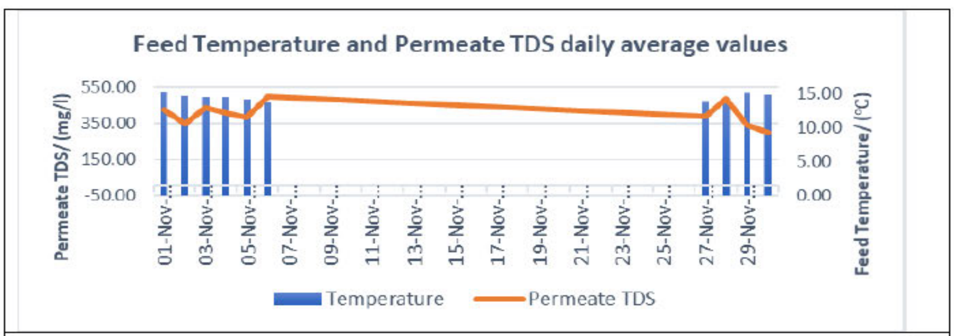
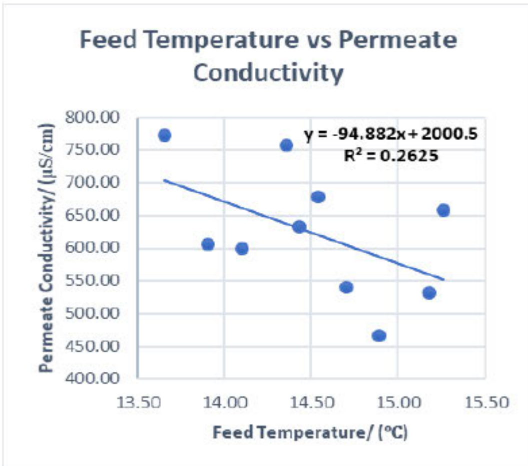


Figure 15: Average Experimental Day Values of Feed Temperature and Permeate TDS.

Below are graphs of feed water temperature against several parameters. The graph of feed temperature vs permeate conductivity, Figure 16, shows a general decrease in permeate conductivity levels as the feed temperature increases.



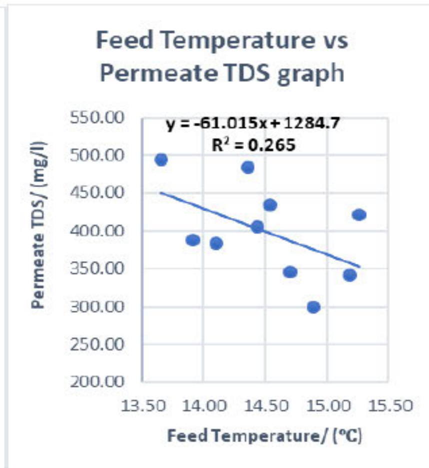


Figure 16: The Relationship between Feed Water Temperatures Figure 17 The Effects of Permeate Temperature on permeate TDS and Permeate Conductivity.

The experimental results that were obtained on the last day showed the variation that followed the trendline observed in Figure 16. A decrease in permeate TDS was recorded as feed temperature increased. Figure. 17 shows the November 2018 experiment results.

5.4 The Effects of Feed Pressure

Research has shown that as pressure increases, percentage recovery increases and specific energy decreases [30]. Increasing feed temperature leads to a decrease in feed pressure requirements, leading to a decrease in production cost. This has a negative effect on recovery ratio as it tends to decrease with a decrease in feed pressure [31]. The average daily values of feed pressure and permeate TDS is shown in Figure 18 while Figure 19 shows the effects of feed pressure on permeate TDS for the plant.

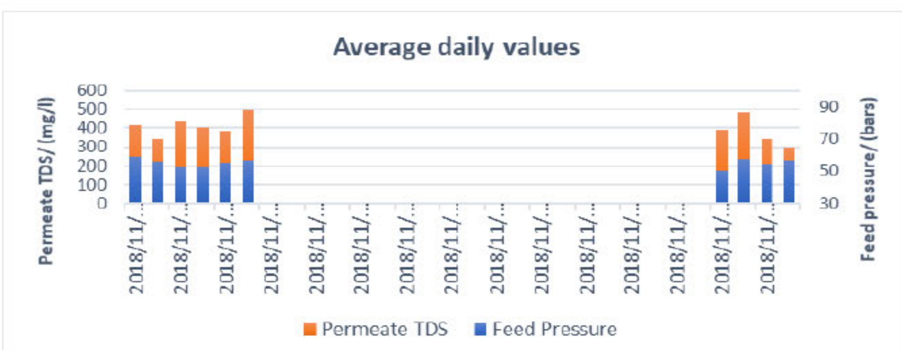


Figure 18: Average Daily values of Permeate TDS and Feed Pressure.

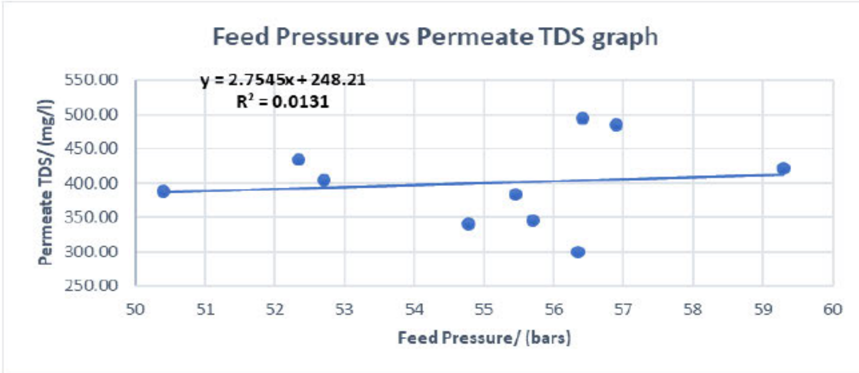
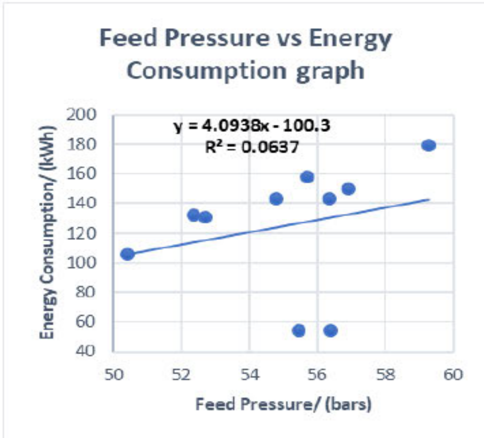


Figure 19 Permeate TDS as a Function of Feed Pressure.

5.5 The Effects of Feed Temperature, Pressure and TDS on Specific Energy Consumption (SEC)

Specific energy consumption is one of the most important parameters of RO desalination. High values of SEC are the main barriers of expansion of SWRO desalination therefore reduction of this parameter is key [5]. Kim et al. [19] concluded that if feed temperature is increased, the net driving pressure decreases. An increase in feed temperature (decrease in net driving pressure) will also result in a reduction in energy consumption of the plant [20]. SEC is also affected by feed pressure. An increase in operating pressure significantly decreases SEC [32]. To increase the efficiency of energy consumption, recovery devices are employed so that pressure is recovered from the concentrate [5]. The efficiency of high pressure pumps and energy recovery devices is also affected by the feed temperature. An increase in temperature tends to reduce the efficiency of these mechanical devices [33]. High feed TDS increases SEC owing to the increased hydraulic pressure necessary to overcome the high osmotic pressure [5], thereby increasing the cost of production [34]. Figure 20 to Figure 26 show the effects of different input parameters on energy consumption of the plant. Feed pressure, feed TDS and feed pH tend to increase the energy consumption as these parameters increase as shown in Figure 20, Figure 21 and Figure. 22 respectively. Figure 24, Figure 25 and Figure 26 represent the bar graphs of power consumption and feed pressure, feed TDS and feed temperature daily average values respectively. It can be deduced that as feed TDS increases, power consumption will generally increase. This is due to the increase in high feed pressure needed to overcome the high osmotic pressure.



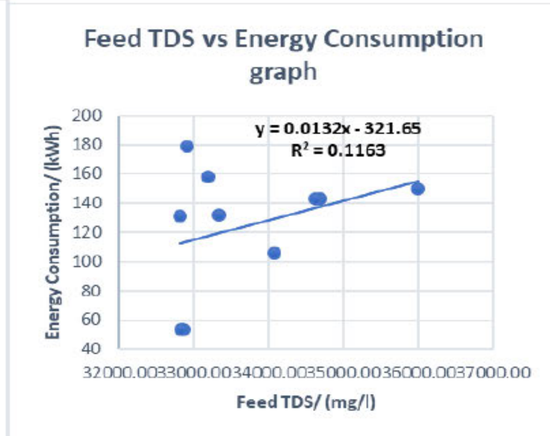
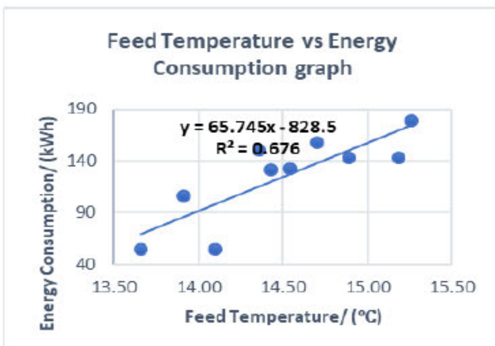


Figure 20: Interaction Plots for Feed Pressure and Energy Consumption.
Figure 21: Feed TDS and Energy Consumption Correlation



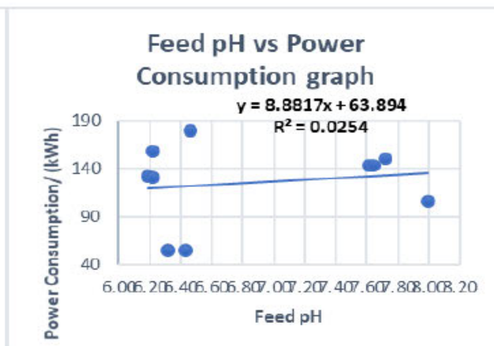


Figure 22: Relationship between Feed Temperature and Energy Consumption:
Figure 23: Power Consumption as a Function of Feed pH.

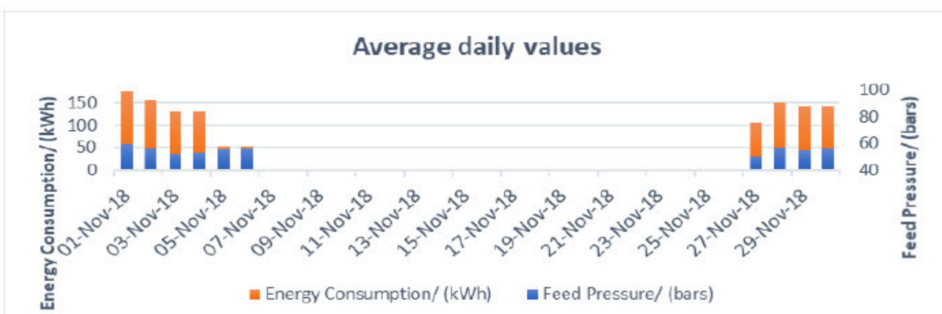


Figure 24: Daily Average Values of Feed Pressure and Energy Consumption.

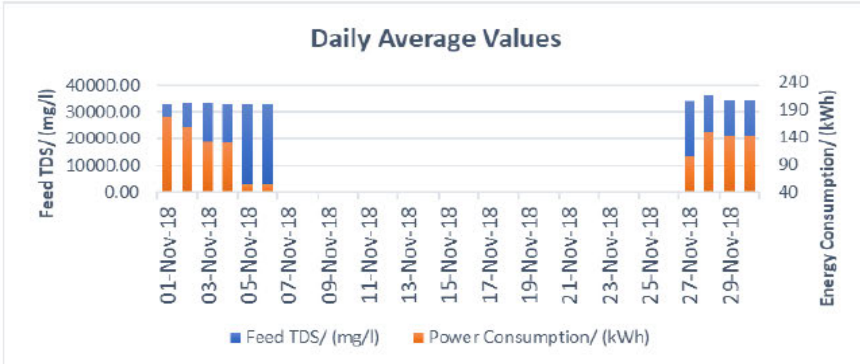


Figure 25: Average Daily Values of Feed TDs and Energy Consumption.

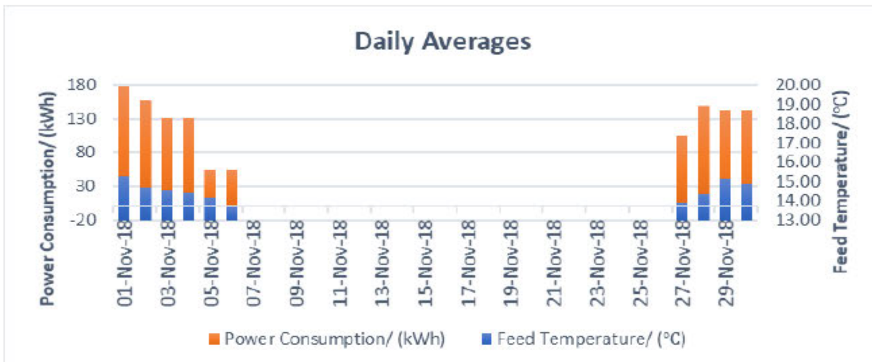


Figure 26: Power Consumption and Feed Temperature Daily Average Figures.

6. DISCUSSIONS

The graphs in Figure 10 and Figure 11 show a general decrease in permeate TDS and conductivity as pH increases. A hypothetical regression shows a strong positive correlation between pH and permeate conductivity. This is certified by Vaseghi et al. (2016) who stated that pH varies inversely with permeate TDS and conductivity. A higher pH results in a lower product ion concentration. [7]. Research conducted by Su et al. (2017) found that feed pH has a slight effect on permeate TDS in extreme cases of pH, that is, when the pH is acidic and basic. The research showed an increase in ion rejection with an increase in pH [35]. Several dynamic pH experiments show a stable permeate flux and higher TDS rejection at low pH, nevertheless, the overall permeate flux is generally higher at high pH [36]. Figure 16 and Figure. 17 show a general decrease in permeate conductivity and TDS as temperature increases. This follows a trend that when the temperature of water increases there is a subsequent increase in the water permeability coefficient and the salt permeability coefficient of the membrane [5, 37]. This increase in temperature leads to a decrease in water viscosity, which in turn leads to membranes becoming more permeable [20] and also in the increase of permeate flux [31]. Recent research has found that both permeate concentration and flow rate increase with an increase in temperature resulting in an increase in recovery and subsequently, an increase in the mechanical power consumed [21]. According to Guler (2019), a decrease in temperature reduces the conductivity and turbidity but increases the mineral rejection of the permeate water [29]. Feed TDS vs permeate TDS is plotted in the graph shown in Fig. 14. The graph shows a slight decrease in the permeate TDS as feed TDS is increased. For higher feed TDS, the permeate may surpass normal design limits, but if lower permeate TDS is required, an increase in permeate flux is employed [38]. An increase in feed concentration leads to a reduction in permeate flux due to the increase in salt concentration polarization that tends to add more resistance to membrane vapour permeation. High TDS also results in membrane surface fouling and scaling thereby reducing the effective area, ultimately reducing the membrane flux [39]. This will lead to an increase in permeate TDS and conductivity [7].

The graph of feed pressure against permeate TDS shows that as pressure is increased, the permeate TDS slightly increases. An increase in feed pressure leads to an increase in the recovery rate, that is, a higher flowrate on the permeate side is observed as compared to the concentrate side. This results in an accumulation of the rejected salts in the membrane surfaces causing surface concentration and mass transfer in the surfaces. This will lead to an increase in concentration polarization resulting in low permeate quality [40]. On the other hand, Gandhidasan and Al-Mojel (2009) [30], found that as feed pressure increases, permeate TDS decreases. Fig. 20 and Fig. 21 show the interaction plots for feed pressure and feed TDS against energy consumption respectively. The graphs show a general increase in energy consumption as the two variables increase. According to Omkar et al. (2018), an increase in feed TDS results in an increase in energy consumption due to the reduction in the recovery rate [41]. High feed TDS increases energy consumption owing to the high hydraulic pressure required to overcome the high osmotic pressure [5, 42], thereby increasing the cost of production [34]. According to Runhong Du et al. (2020), increasing pressure will increase the energy consumed and also reduce the membrane life [43]. In contrast, Fig. 21 shows an increase in feed pressure. This tends to have a negative effect on power consumption. An increase in power consumption is observed due to an increase in recovery rate [37]. According to Fig. 22, an increase in feed temperature results in an increase in energy consumption of the plant. This is in agreement with research conducted by Sarai et al. (2016) where an increase in temperature leads to an increase in recovery rate leading to an increase in mechanical power consumption [21]. Kim et al. (2019) also stated that the minimum amount of energy required for desalination increases slightly with an increase in temperature, thereby slightly increasing the energy consumption [5].

7. CONCLUSIONS

The experiments conducted at the Waterfront desalination plant showed results that were somewhat expected from a desalination unit of that magnitude. The results showed a general decrease in permeate TDS as feed pH and feed temperature increased. This is due to the decrease in water viscosity as temperature increases, leading to more permeable membranes hence the reduction in permeate TDS. The results also showed a generally slight increase in permeate TDS with an increase in pressure. This is so because increasing pressure has a negative effect on the recovery ratio. In as much as an increase in pressure leads to lower costs, there is a need to optimize the feed pressure so as not to compromise the quality of permeate water produced.

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REFERENCES

1. *1.Choi, J.-S. and J.-T. Kim, Modeling of full-scale reverse osmosis desalination system: Influence of operational parameters. Journal of Industrial and Engineering Chemistry,* ***21:*** *2015. pp. 261-268 DOI: https://doi.org/10.1016/j.jiec.2014.02.033*

2. Randy Ncube & Professor Freddie L. Inambao,"Theoretical Data Analysis for a Small-Scale Reverse Osmosis Desalination Plant",International Journal of Mechanical and Production Engineering Research and Development (IJMPERD),Vol. 11, Issue 2,pp, 31-40

3. Khalil, K.H., F.M. Wali, and A.M. El-Dosarit, Operational performance and monitoring of a reverse osmosis desalination lant: A case study. International Journal of Current Engineering and Technology, **5**(6): 2015. pp. 3760. Available from: https://www.researchgate.net/profile/Farouk-Wali-2/publication/286928558_Operational_Performance_and_Monitoring_of_a_Reverse_Osmosis_Desalination_Plant_A_Case_Study/links/567051cb08ae5252e6f1de01/Operational-Performance-and-Monitoring-of-a-Reverse-Osmosis-Desalination-Plant-A-Case-Study.pdf

4. Dipti G. Wankhade & Sanjay M. Chavan, "Studies on Concentration Polarization for Purification of Saline Water Using Spiral Wound Reverse Osmosis Module",International Journal of Chemical & Petrochemical Technology (IJCPT),Vol. 5, Issue 1, pp, 11-18

5. Qasim, M., M. Badrelzaman, N.N. Darwish, N.A. Darwish, and N. Hilal, Reverse osmosis desalination: A state-of-the-art review. Desalination, **459**: 2019. pp. 59-104 DOI: https://doi.org/10.1016/j.desal.2019.02.008

6. S. R. Kalbande, Priyanka Nayak, Sneha Deshmukh & V. P. Khambalkar, "Thermal Evaluation of Solar Water Desalination System with Evacuated Tubes", International Journal of Applied and Natural Sciences (IJANS),Vol. 6, Issue 1,pp; 41-54

7. Altaee, A., A. Sharif, G. Zaragoza, and A.F. Ismail, Evaluation of FO-RO and PRO-RO designs for power generation and seawater desalination using impaired water feeds. Desalination, **368**: 2015. pp. 27-35 DOI: https://doi.org/10.1016/j.desal.2014.06.022

8. D. Sumathi,"Sea Water Desalination Plant – A Water Resource Management In Tamil Nadu",IMPACT: International Journal of Research in Humanities, Arts and Literature (IMPACT: IJRHAL),Vol. 3, Issue 5,pp, 139–142

9. Kim, J., K. Park, D.R. Yang, and S. Hong, A comprehensive review of energy consumption of seawater reverse osmosis desalination plants. Applied Energy, **254**: 2019. pp. 113652 DOI: https://doi.org/10.1016/j.apenergy.2019.113652

10. Sassi, K.M. and I.M. Mujtaba, Simulation and optimization of full scale reverse osmosis desalination plant. Computer Aided Chemical Engineering. **28**: 2010, pp. 895-900. https://doi.org/10.1016/S1570-7946(10)28150-6

11. Vaseghi, G., A. Ghassemi, and J. Loya, Characterization of reverse osmosis and nanofiltration membranes: effects of operating conditions and specific ion rejection. Desalination and Water Treatment, **57**(50): 2016. pp. 23461-23472 DOI: https://doi.org/10.1080/19443994.2015.1135825.

12. Brehant, A., V. Bonnelye, and M. Perez, Comparison of MF/UF pretreatment with conventional filtration prior to RO membranes for surface seawater desalination. Desalination, **144**(1-3): 2002. pp. 353-360 DOI: https://doi.org/10.1016/S0011-9164(02)00343-0

13. Valavala, R., J. Sohn, J. Han, N. Her, and Y. Yoon, Pretreatment in reverse osmosis seawater desalination: A short review. Environmental Engineering Research, **16**(4): 2011. pp. 205-212 DOI: https://doi.org/10.4491/eer.2011.16.4.205

14. Jamaly, S., N. Darwish, I. Ahmed, and S. Hasan, A short review on reverse osmosis pretreatment technologies. Desalination, **354**: 2014. pp. 30-38 DOI: https://doi.org/10.1016/j.desal.2014.09.017.

15. Knops, F., S. van Hoof, H. Futselaar, and L. Broens, Economic evaluation of a new ultrafiltration membrane for pretreatment of seawater reverse osmosis. Desalination, **203**(1-3): 2007. pp. 300-306 DOI: https://doi.org/10.1016/j.desal.2006.04.013

16. Gude, V.G., Energy consumption and recovery in reverse osmosis. Desalination and Water Treatment, **36**(1-3): 2011. pp. 239-260 DOI: https://doi.org/10.5004/dwt.2011.2534

17. Sutzkover-Gutman, I. and D. Hasson, Feed water pretreatment for desalination plants. Desalination, **264**(3): 2010. pp. 289-296 DOI: https://doi.org/10.1016/j.desal.2010.07.014

18. Bonnélye, V., L. Guey, and J. Del Castillo, UF/MF as RO pre-treatment: the real benefit. Desalination, **222**(1-3): 2008. pp. 59-65 DOI: https://doi.org/10.1016/j.desal.2007.01.129

19. Peñate, B. and L. García-Rodríguez, Current trends and future prospects in the design of seawater reverse osmosis desalination technology. Desalination, **284**: 2012. pp. 1-8 DOI: https://doi.org/10.1016/j.desal.2011.09.010

20. Lee, K.P., T.C. Arnot, and D. Mattia, A review of reverse osmosis membrane materials for desalination—development to date and future potential. Journal of Membrane Science, **370**(1-2): 2011. pp. 1-22 DOI: https://doi.org/10.1016/j.memsci.2010.12.036

21. Altaee, A. and A. Sharif, A conceptual NF/RO arrangement design in the pressure vessel for seawater desalination. Desalination and Water Treatment, **54**(3): 2015. pp. 624-636 DOI: https://doi.org/10.1080/19443994.2014.890547

22. Johnson, J. and M. Busch, Engineering aspects of reverse osmosis module design. Desalination and Water Treatment, **15**(1-3): 2010. pp. 236-248 DOI: https://doi.org/10.5004/dwt.2010.1756

23. Kim, S.J., S. Oh, Y.G. Lee, M.G. Jeon, I.S. Kim, and J.H. Kim, A control methodology for the feed water temperature to optimize SWRO desalination process using genetic programming. Desalination, **247**(1-3): 2009. pp. 190-199 DOI: https://doi.org/10.1016/j.desal.2008.12.024

24. Nisan, S., B. Commercon, and S. Dardour, A new method for the treatment of the reverse osmosis process, with preheating of the feedwater. Desalination, **182**(1-3): 2005. pp. 483-495 DOI: https://doi.org/10.1016/j.desal.2005.02.041

25. Atab, M.S., A. Smallbone, and A. Roskilly, An operational and economic study of a reverse osmosis desalination system for potable water and land irrigation. Desalination, **397**: 2016. pp. 174-184 DOI: https://doi.org/10.1016/j.desal.2016.06.020

26. Assad, M.E.H., M. Al-Shabi, and F. Khaled. Reverse osmosis with an energy recovery device for seawater desalination powered by geothermal energy. in 2020 Advances in Science and Engineering Technology International Conferences (ASET). pp. 1-5. IEEE.

27. Swartz, C., J. Du Plessis, A. Burger, and G. Offringa, A desalination guide for South African municipal engineers. Water SA, **32**(5): 2006 DOI: 10.4314/wsa.v32i5.47845.

28. Gilabert Oriol, G., M. Hassan, J. Dewisme, M. Busch, and V. Garcia-Molina, High efficiency operation of pressurized ultrafiltration for seawater desalination based on advanced cleaning research. Industrial & Engineering Chemistry Research, **52**(45): 2013. pp. 15939-15945 DOI: https://doi.org/10.1021/ie402643z

29. Quality Filtration System. V&A Waterfront Desalination Plant. 2017; Available from: https://www.qualityfilters.co.za/portfolio/va-waterfront-desalination-plant/.

30. Huang, B., K. Pu, P. Wu, D. Wu, and J. Leng, Design, selection and application of energy recovery device in seawater desalination: A review. Energies, **13**(16): 2020. pp. 4150 DOI: https://doi.org/10.3390/en13164150

31. Cameron, I.B. and R.B. Clemente, SWRO with ERI's PX Pressure Exchanger device—a global survey. Desalination, **221**(1-3): 2008. pp. 136-142 DOI: https://doi.org/10.1016/j.desal.2007.02.050

32. Kim, S.J., Y.G. Lee, S. Oh, Y.S. Lee, Y.M. Kim, M.G. Jeon, S. Lee, I.S. Kim, and J.H. Kim, Energy saving methodology for the SWRO desalination process: control of operating temperature and pressure. Desalination, **247**(1-3): 2009. pp. 260-270 DOI:

https://doi.org/10.1016/j.desal.2008.12.006

33. Guler, E., J. Piekacz, D. Ozakdag, W. Kujawski, M. Arda, M. Yuksel, and N. Kabay, Influence of the chosen process parameters on the efficiency of seawater desalination: SWRO pilot plant results at Urla Bay seashore. Desalination and Water Treatment, **5**(1-3): 2009. pp. 167-171 DOI: https://doi.org/10.5004/dwt.2009.586
34. Gandhidasan, P. and S.A. Al-Mojel, Effect of feed pressure on the performance of the photovoltaic powered reverse osmosis seawater desalination system. Renewable Energy, **34**(12): 2009. pp. 2824-2830 DOI: https://doi.org/10.1016/j.renene.2009.04.029
35. Sassi, K.M. and I.M. Mujtaba, Effective design of reverse osmosis based desalination process considering wide range of salinity and seawater temperature. Desalination, **306:** 2012. pp. 8-16 DOI: https://doi.org/10.1016/j.desal.2012.08.007
36. Wang, Q., Z. Zhou, J. Li, Q. Tang, and Y. Hu, Investigation of the reduced specific energy consumption of the RO-PRO hybrid system based on temperature-enhanced pressure retarded osmosis. Journal of Membrane Science, **581:** 2019. pp. 439-452 DOI: https://doi.org/10.1016/j.memsci.2019.03.079
37. Koutsou, C., E. Kritikos, A. Karabelas, and M. Kostoglou, Analysis of temperature effects on the specific energy consumption in reverse osmosis desalination processes. Desalination, **476:** 2020. pp. 114213 DOI: https://doi.org/10.1016/j.desal.2019.114213
38. Yusefi, F., M.M. Zahedi, and M. Ziyaadini, Evaluation for the optimization of two conceptual 200,000 m 3/day capacity RO desalination plant with different intake seawater of Oman Sea and Caspian Sea. Applied Water Science, **11**(2): 2021. pp. 1-10 DOI: https://doi.org/10.1007/s13201-020-01338-5
39. Su, X., Y. Song, T. Li, and C. Gao, Effect of feed water characteristics on nanofiltration separating performance for brackish water treatment in the Huanghuai region of China. Journal of Water Process Engineering, **19:** 2017. pp. 147-155 DOI: https://doi.org/10.1016/j.jwpe.2017.07.021.
40. Sadrzadeh, M., J. Hajinasiri, S. Bhattacharjee, and D. Pernitsky, Nanofiltration of oil sands boiler feed water: Effect of pH on water flux and organic and dissolved solid rejection. Separation and Purification Technology, **141:** 2015. pp. 339-353 DOI: https://doi.org/10.1016/j.seppur.2014.12.011
41. Alsarayreh, A.A., M. Al-Obaidi, A. Al-Hroub, R. Patel, and I. Mujtaba, Evaluation and minimisation of energy consumption in a medium-scale reverse osmosis brackish water desalination plant. Journal of Cleaner Production, **248:** 2020. pp. 119220 DOI: https://doi.org/10.1016/j.jclepro.2019.119220
42. Busch, M. and W. Mickols, Reducing energy consumption in seawater desalination. Desalination, **165:** 2004. pp. 299-312 DOI: https://doi.org/10.1016/j.desal.2004.06.035
43. Khalifa, A., H. Ahmad, M. Antar, T. Laoui, and M. Khayet, Experimental and theoretical investigations on water desalination using direct contact membrane distillation. Desalination, **404:** 2017. pp. 22-34 DOI: https://doi.org/10.1016/j.desal.2016.10.009.
44. Lee, J.J., Y.C. Woo, and H.-S. Kim, Effect of driving pressure and recovery rate on the performance of nanofiltration and reverse osmosis membranes for the treatment of the effluent from MBR. Desalination and Water Treatment, **54**(13): 2015. pp. 3589-3595 DOI: https://doi.org/10.1080/19443994.2014.923196
45. Lokare, O.R., S. Tavakkoli, V. Khanna, and R.D. Vidic, Importance of feed recirculation for the overall energy consumption in membrane distillation systems. Desalination, **428:** 2018. pp. 250-254 DOI: https://doi.org/10.1016/j.desal.2017.11.037

46. *Ghaffour, N., J. Bundschuh, H. Mahmoudi, and M.F. Goosen, Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications of integrated systems. Desalination,* ***356:*** *2015. pp. 94-114 DOI: https://doi.org/10.1016/j.desal.2014.10.024*

47. *Du, J.R., X. Zhang, X. Feng, Y. Wu, F. Cheng, and M.E. Ali, Desalination of high salinity brackish water by an NF-RO hybrid system. Desalination,* ***491:*** *2020. pp. 114445 DOI: https://doi.org/10.1016/j.desal.2020.114445*

CHAPTER 8. Modeling, Simulation and Optimization of the Reverse Osmosis Desalination Plant

Modeling, simulation and optimization of the V & A desalination plant was performed using experimental data extracted from the plant and some assumed data. Mathematical modeling was assumed to be following the basic principles and equations of mass and transport theory. Simulation and optimization was accomplished using Water Application Value Engine simulation software and improvements in specific energy consumption, permeate TDS and permeate productivity were observed. This article was accepted for publication in the International Journal of Mechanical and Production Engineering Research and Development (IJMPERD).

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Original Article

MODELING, SIMULATION AND OPTIMIZATION OF A REVERSE OSMOSIS DESALINATION PLANT

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ABSTRACT

Reverse osmosis modeling and simulation is essential in the design of a seawater reverse osmosis desalination plant. Proper procedures will result in designs that will help engineers and designers to come up with optimized plants. This article gives modeling, simulation and optimization of the V & A desalination plant located in Cape Town, South Africa. Mathematical modeling was assumed to be following the basic principles and equations of mass and transport theory. Simulation and optimization were accomplished using Water Application Value Engine simulation software. The optimization results showed a 7.3 % improvement in specific energy consumption (SEC) and about 18 % improvement in permeate productivity using the same membranes, recovery rate and feed total dissolved solids.

KEYWORDS: Desalination, Reverse Osmosis, Modeling, Simulation, Optimization & WAVE Software

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1. INTRODUCTION

Potable water scarcity is proving to be a global problem as the number of people with inadequate supply of fresh water keeps on increasing. South Africa is also faced with this problem. The drought in 2018 was the worst recorded in the country, and the city of Cape Town is now exploring alternative sources of potable water supply and water management systems (Enqvist & Ziervogel, 2019). One of the alternatives is desalination of brackish and seawater, particularly by means of seawater reverse osmosis (SWRO) desalination. RO has taken leadership in the desalination market (Lappalainen et al., 2017). At least 60 % of the world's total installed desalination plants are RO operated (Ahmed et al., 2019). RO plant performance is sensitive to input parameters such as feed water quality and operating conditions (Oh et al., 2009). Energy consumption is one of the most important parameters that is still relatively high in the RO desalination process and this needs to be minimized. Optimization of the plants that are in operation is one of the ways that will help in minimizing the SEC, at the same time optimizing the desalination system. This paper seeks to develop a software-based model for simulation and optimization with respect to the already operational plant.

2. MODELING OF THE PLANT

Modeling is a procedure in which mathematical equations are used to describe real-life problems so as to solve these problems more easily (Ahmed et al., 2019). RO modeling, if done properly, will result in fewer experiments needing to be undertaken, thereby reducing time and costs associated with desalination (Ang & Mohammad, 2015). Several modeling techniques are applied to come up with mathematical relationships between the different parameters. Membrane modeling software is often used to estimate the performance of the system but is limited to membranes that are designed by a specific company. Coupling of different software or membrane manufacturers is not possible yet (Altaee, 2012). Modeling of the RO plant in this study follows the following assumptions:

- The pressure drop is neglected along the membrane channel.
- Spiral wound elements are treated as flat.
- The concentration of feed linearly varies along the feed channel (Sassi & Mujtaba, 2010).

This section assumes that the plant follows the modeling equations that are listed in the equations below. In the solution diffusion model, permeate flow rate, Q_w, is calculated using Eq. 1:

$$Q_w = A(\Delta P - \Delta\pi) \quad \text{(Eq. 1)}$$

Where ΔP is feed and permeate pressure difference and $\Delta\pi$ is osmotic pressure (Ahmed et al., 2019; Kim, Oh et al., 2009; Oh et al., 2009).

Osmotic pressure, $\Delta\pi$ equation is given by Eq. 2:

$$\Delta\pi = n_i C R_g T \quad \text{(Eq. 2)}$$

Where n_i, R_g and T represent number of moles of species, universal gas constant 0.082 kg.m^2/h^2.K and feed temperature respectively.

The recovery ratio, K, is given by Eq. 3:

$$K = \frac{Q_p}{Q_f} \quad \text{(Eq. 3)}$$

Where Q_p is permeate flow and Q_f is feed flow. The recovery ratio tends to decrease with an increase in feed total dissolved solids (TDS) at a given temperature (Nisan et al., 2005).

The temperature correlation factor (TCF) for a given RO plant is calculated by Eq. 4:

$$TCF = e^{\left[\frac{Em}{R}\left(\frac{1}{273+T} - \frac{1}{298}\right)\right]} \quad \text{(Eq. 4)}$$

Where E_m is membrane activation energy, R is gas constant and T is temperature (Atab et al., 2016).

The theoretical calculations of SEC and permeate flux (J_v) are given by Eq. 5 and Eq. 6 respectively (Assad et al., 2020):

$$SEC = \frac{E_{bp} + E_{hp} + E_{sp}}{Q_p} \quad \text{(Eq. 5)}$$

$$J_v = \frac{Q_p}{A} \quad \text{(Eq. 6)}$$

Where: E_{bp}, E_{hp} and E_{sp} are energies consumed by the booster pump, high pressure pump and supply pump respectively, and Q_p and A represent the permeate water flow rate and area of membrane respectively.

Salt rejection, R_s, and total mass balance, $Q_f C_f$ are calculated respectively by Eq. 7 and Eq. 8. Permeate water flow rate is calculated by Eq. 9 and Eq. 10:

$$R_s = 1 - \frac{TDS_p}{TDS_f} \quad \text{(Eq. 7)}$$

$$Q_f C_f = Q_p C_p - Q_r C_r \quad \text{(Eq. 8)}$$

$$Q_p = Q_f - Q_r \quad \text{(Eq. 9)}$$

$$Q_p = n_i W \int_0^L J_v dz \quad \text{(Eq. 10)}$$

Where C_f, C_p and C_r are feed, permeate and reject salts mass concentrations respectively, Q_r is reject water flow rate and n_i, L and W represent number of leaves, length and width of the RO module.

Accordingly, solvent flux, J_v, and solute flux, J_s follow the following expressions:

$$J_v = A_w\left(P_f - P_d - P_p - \Delta\pi\right) \quad \text{(Eq. 11)}$$

$$J_s = B_S(C_m - C_b) \quad \text{(Eq. 12)}$$

Where A_w represents the solvent transport parameter, P_f, P_d and P_p represent feed pressure, pressure drop along the membrane and permeate pressure (Ang & Mohammad, 2015; Jiang et al., 2014; Swartz et al., 2006).

Impermeable salt accumulation on membrane surfaces leads to concentration polarization, ϕ, given by Eq. 13:

$$\emptyset = \frac{C_m - C_p}{C_b - C_p} = e^{\frac{Jv}{k}} \quad \text{(Eq. 13)}$$

Where C_b is bulk solution solute concentration and k is the mass transfer concentration (Lee et al., 2010).

Normalized Temperature, TMP*:

$$TMP^* = TCF * TMP \quad \text{(Eq. 14)}$$

Temperature correction factor (TCF) is a factor that takes into cognisance the effect of the temperature (Gilabert Oriol et al., 2013).

Specific energy consumption (SEC) of the plant is calculated using Eq. 15 and Eq. 16 respectively:

$$SEC = \frac{W_{pump}}{Q_p} \quad \text{(Eq. 15)}$$

$$W_{pump} = \frac{\Delta P * Q_f}{\eta_{pump}} \quad \text{(Eq. 16)}$$

Where W_{pump} is the work done by the pump and η_{pump} is the pump efficiency (Zarai et al., 2013).

3. SIMULATION

In the following section, the above modeling equations are applied to the simulations performed. Simulation was conducted on the data using DuPont powered Water Application Value Engine (WAVE) software, modeling software for water treatment plant design. WAVE is a fully integrated modeling software that integrates three main leading water treatment technologies. These include reverse osmosis (RO), ultrafiltration (UF) and ion exchange (IU) (DuPont, 2021). The software combines the previous software features of reverse osmosis system analysis (ROSA), offering improved and consistent algorithms, improved mass balance and flow resulting from temperature changes, water characteristics and water compressibility and sharing of designs is also possible (Edina, 2017).

Simulations for the 100-10 train were carried out. Most of the variables were extracted from experimental values and some of the values were assumed before performing the simulations. One of the parameters assumed was the permeate water flow, $Q_{permeate}$. The assumption was that all three trains produce equal amounts of permeate water, therefore the total permeate flow rate of 1 367 m^3/d was divided into three equal parts, resulting in each train producing approximately 460 m^3/d or 20 m^3/h. DOW SW30 ULE 440i membranes are now obsolete therefore all the membranes were assumed to be DOW SW30 XLE 440i. Table 1 shows experimental values and assumptions made on the plant.

Table 1: Assumed and Experimentally Extracted Values for Different Parameters

Parameter	Assumed Value	Experimental Value
Q_{feed} [m^3/d (m^3/h)]	460 (20)	
$Q_{permeate}$ [m^3/d (m^3/h)]	1480 (62)	
Average temperature, (T/ °C)	14.5	
Average pH	7.2	
Average pressure (P/ bars)	55	
Recovery (%)		31
Feed TDS (mg/l)		33728
DOW SW30 XLE 440i	7 membranes	
DOW SW30 ULE 440i		(Obsolete)
No. of vessels		6

Table 2: Simulated Results of the V & A Desalination Plant

Parameter	V & A Desalination Plant	Simulated Value	Error (%)
Permeate flow (m^3/h)	19	20	5
Feed TDS (mg/l)	33 728.88	33 619	0.3
Permeate TDS (mg/l)	399.79	104	73
Feed pressure (bars)	55	46.7	15
Energy consumption (kW/h)	6.58	5.68	13.7
Peak power (kW)	125	113.5	9.2
Recovery (%)	31	31	0
Rejection (%)	98.81	99.69	0.9

The schematic diagram and the description of variables of the simulated results are shown in Figure 1. and Table 3 respectively. Stage 1 shows the raw feed water inlet and stage 2 shows the pressurized feed water to the RO vessels. Stages 3, 4 and 5 indicate concentrate water. Some of the concentrate is recycled back to feed water (stage 3) whilst some of the concentrate is discarded as waste (Stage 5). Stage 6 shows the permeate (potable water). At every stage of the simulation, TDS and pressures are recorded. Feed pressure is recorded as 46.4 bar (stage 2) compared to the experimental value of 55 bar.

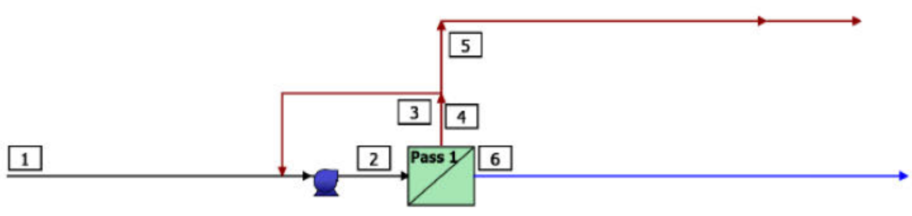


Figure 1: Schematic Diagram of the Simulated Design.

Table 3: Description of Different Stages of Simulation and their Corresponding Values

#	Description	Flow (m^3/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	64.5	33,619	0.0
2	Net Feed to Pass 1	69.3	34,750	46.4
3	Concentrate Recycle from Pass 1 to Pass 1	4.94	48,751	43.6
4	Total Concentrate from Pass 1	49.4	48,751	43.6
5	Net Concentrate from RO System	44.4	48,751	43.6
6	Net Product from RO System	20.0	117.8	0.0

A summary of the simulation results system overview and flow table is shown in Tables 4 and 5 respectively. These results show several deviations to the values extracted from the actual plant. Ideal SEC was recorded as 5.6 kWh/m^3, while the actual SEC of the plant is 6.58 kW/h, a higher value. An average flux of 11.6 LMH and permeate TDS of 117.8 mg/l was recorded.

Table 4: RO System Overview

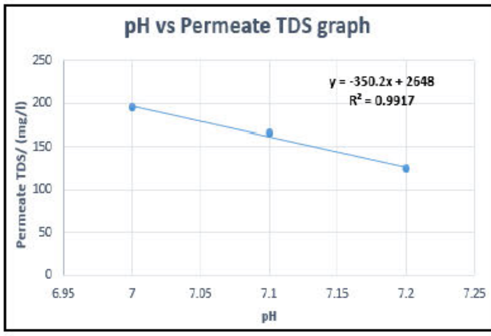
Pass		Pass 1
Stream Name		Stream 1
Water Type		Sea Water (With conventional pretreatment, SDI < 5)
Number of Elements		42
Total Active Area	(m^2)	1717
Feed Flow per Pass	(m^3/h)	69.3
Feed TDS[a]	(mg/L)	34,750
Feed Pressure	(bar)	46.4
Flow Factor Per Stage		0.85
Permeate Flow per Pass	(m^3/h)	20.0
Pass Average flux	(LMH)	11.6
Permeate TDS[a]	(mg/L)	117.8
Pass Recovery		28.9%
Average NDP	(bar)	13.3
Specific Energy	(kWh/m^3)	5.60
Temperature	(°C)	16.0
pH		7.2
Chemical Dose		-
RO System Recovery		31.0%
Net RO System Recovery		31.0%

Table 5: RO Flow Table

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow (m^3/h)	Recirc Flow (m^3/h)	Feed Press (bar)	Boost Press (bar)	Conc Flow (m^3/h)	Conc Press (bar)	Press Drop (bar)	Perm Flow (m^3/h)	Avg Flux (LMH)	Perm Press (bar)	Perm TDS (mg/L)
1	SW30XLE-440i	6	7	69.3	4.94	46.0	0.0	49.4	43.6	2.5	20.0	11.6	3.0	117.8

A detailed report on the simulation is provided in Appendix A. This includes the behavior of each RO element (membrane) during the operation, several solute concentrations, electricity costs, utility and specific water costs.

The following section is dedicated to graphs that were obtained from the WAVE simulation project (Figure. 2 to Figure 6).



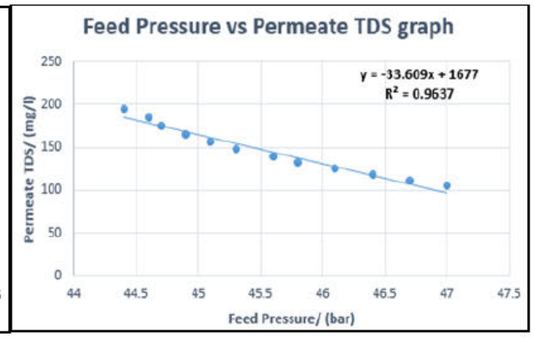
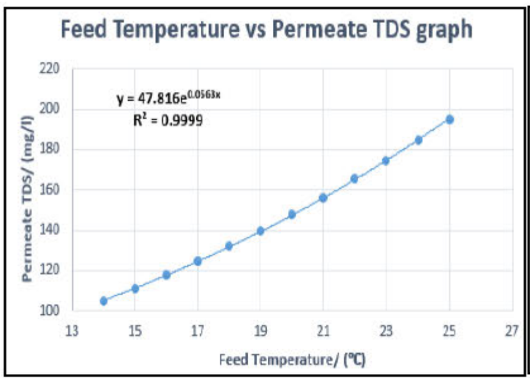


Figure 2: pH vs Permeate TDS Graph **Figure 3: Permeate TDS as a Function of Feed Pressure.**



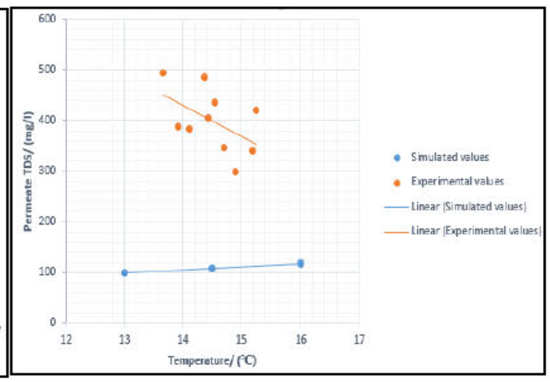


Figure 4: Feed Temperature and Permeate TDS Relationship **Figure 5: Simulated vs Experimental Values of Feed Temperature vs Permeate TDS.**

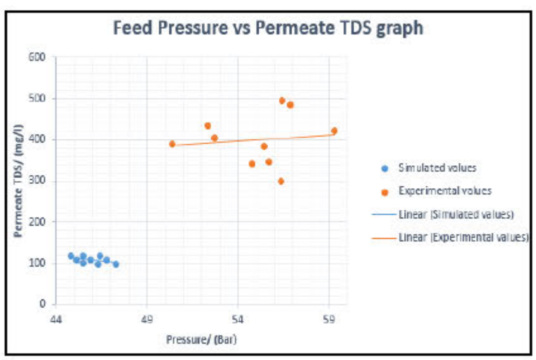


Figure 6: Simulated vs Experimental Values of Feed Pressure vs *Permeate TDS.*

4. OPTIMIZATION

Optimization is a procedure undertaken to come up with the best possible solution to a problem by using different alternatives (Ahmed et al., 2019). Some of the optimization techniques include the genetic algorithm (GA) technique

(Poullikkas, 2001; Murthy & Vengal, 2006; Djebedjian et al., 2008), artificial neural network (ANN) based modeling (established by Libotean et al., 2009). Optimization of the energy consumption is one of the key parameters as energy consumption accounts for 50 % to 60 % of total costs (Ahmed et al., 2019). Parameters like feed pressure and operational temperature as well as membrane properties affect the performance of RO process (Jiang et al., 2014).

Djebedjian et al. (2008) state that for optimization, the single objective to be maximized, Z, and the constraint used in the RO system, C_p, are given by Eq. 17 and Eq. 18 respectively:

$$Z = Q_w \qquad (Eq. 17)$$

$$C_p \leq C_{p,d_i} \qquad (Eq. 18)$$

If external penalty is used in the conversion of constrained problem to an unconstrained problem, then Z is given by Eq. 19:

$$Z = Q_w - Pen \qquad (Eq. 19)$$

Where Pen is the penalty subtracted from the objective function and is given by Eq. 20:

$$Pen = C_{pen}\left(\frac{C_p}{C_{p,d}} - 1\right) \qquad (Eq. 20)$$

Where C_{pen} represents the penalty function constant (can be as big as 100 000).

From the above equations, objective fuction, Z, is expressed by Eq. 21:

$$Z = \begin{cases} Q_w \; if \; C_p \leq C_{p,d} \\ Q_w - C_{pen} * \left(\frac{C_p}{C_{p,d}} - 1\right) otherwise \end{cases} \qquad (Eq. 21)$$

Sassi and Mujtaba (2011) stated that optimization strategy considering module design and operating parameters is given by the following method:

Given: Membrane properties and specifications and feed water characteristics (conditions),

Optimize: The optimal feed flow, feed pressure and design decisions,

So as to minimize: Specific energy consumption,

And maximize: Permeate flow,

Subject to: Equality and inequality constraints.

Optimization was conducted using the WAVE modeling and optimization software. Optimization of the V & A desalination plant was performed so as to come up with the best combination of variables. The plant was operating at around 68 % of the design capacity, (1 367 m^3/d instead of the design capacity of 2 000 m^3/d). Optimization of the 100-10 train resulted in an increase of the operating capacity to around 86 % capacity, using the same equipment with the same recovery rate of 31 %. Specific energy was improved from 6.58 kWh/m^3 to around 6.1 kWh/m^3, an improvement of around 7.3 %.

The schematic diagram in Figure 1 applies to the optimization of the plant. Feed flow rate was increased to 83.2 m^3/h resulting in a permeate flow rate of 24 m^3/h at a pressure of 50.5 bars compared to the current permeate flow of around 19 m^3/h at 55 bars. Although most of the parameters showed positive changes, specific water costs increased slightly, by 2 %. The summary of input and output parameters is shown in Table 6 and Table 7. Table 6 shows the RO optimization system overview, a set of input parameters, and expected output values. Table 7 depicts the RO optimization flow figures. Appendix B shows a detailed optimization report of the 100-10 plant.

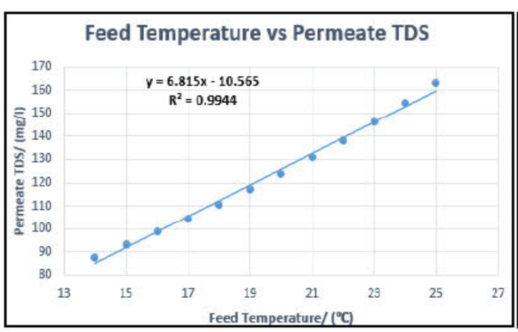
Table 6: RO Optimization System Overview

Pass		Pass 1
Stream Name		Stream 1
Water Type		Sea Water (With conventional pretreatment, SDI < 5)
Number of Elements		42
Total Active Area	(m^2)	1717
Feed Flow per Pass	(m^3/h)	83.2
Feed TDS[a]	(mg/L)	34,752
Feed Pressure	(bar)	50.5
Flow Factor Per Stage		0.85
Permeate Flow per Pass	(m^3/h)	24.0
Pass Average flux	(LMH)	14.0
Permeate TDS[a]	(mg/L)	82.80
Pass Recovery		28.8 %
Average NDP	(bar)	17.3
Specific Energy	(kWh/m^3)	6.10
Temperature	(°C)	15.0
pH		7.3
Chemical Dose		-
RO System Recovery		31.0 %
Net RO System Recovery		31.0%

Table 7: RO Optimization Flow Table

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow (m^3/h)	Recirc Flow (m^3/h)	Feed Press (bar)	Boost Press (bar)	Conc Flow (m^3/h)	Conc Press (bar)	Press Drop (bar)	Perm Flow (m^3/h)	Avg Flux (LMH)	Perm Press (bar)	Perm TDS (mg/L)
1	SW30XLE-440i	6	7	83.2	5.92	50.2	0.0	59.2	46.9	3.4	24.0	14.0	3.0	82.80

The following graphs are the optimization graphs of permeate TDS against feed temperature, feed pressure and feed pH. The graph of permeate TDS and feed temperature (Figure 7) shows a general increase in permeate TDS as temperature increases, while the graph of feed pressure and permeate TDS (Figure. 8) shows a decrease in salt content with respect to an increase in pressure. An increase in pH resulted in a decrease in permeate TDS as shown in Figure. 9.



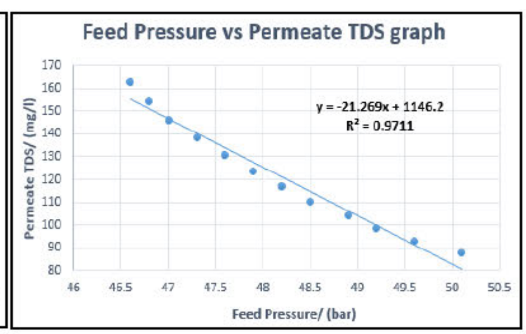


Figure 7: Permeate TDS as a Function of Feed Temperature. Figure 8: Feed Pressure and Permeate TDS Relationship.

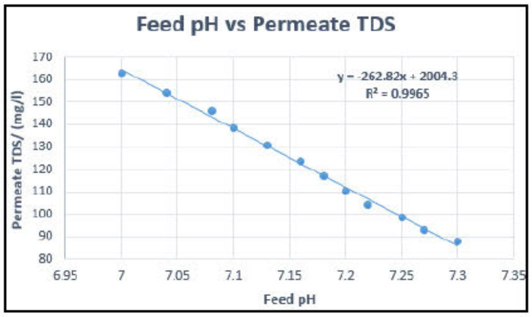


Figure 9: Feed pH Against Permeate TDS Graph.

5. DISCUSSIONS

The main objective of optimization is the minimization of energy consumption of the plant, without compromising the quality of the permeate water. To achieve the theoretical SEC is not possible due to concentration polarization, hydraulic resistance and membrane fouling (Gude, 2011). Optimization of the V & A desalination plant using WAVE software resulted in a decrease of about 13.7 % compared to the experimental value. This decrease in SEC will lead to a reduction in total costs of the plant. The optimization graph on Figure. 7 shows that an increase in temperature resulted in an increase in permeate TDS. This means that a decrease in temperature will result in improved permeate water quality. This is in agreement with Guler et al. (2010) who stated that a decrease in temperature enhances the quality of permeate water. According to Koutsou et al. (2020) increasing temperature of high saline water negatively impacts the salt rejection capabilities of the membranes, hence optimization studies have to be considered. Membrane performance generally decreases with an increase in temperature, thereby increasing the permeate TDS with respect to temperature increase (Kim, Lee et al., 2009; Kim et al., 2020; Kim et al., 1919). This increase in permeate TDS is due to an increase in the viscosity of the water (Kim, Lee et al., 2009) and the expansion of the membrane pores (Atab et al., 2018). Khalifa et al. (2017) are in agreement with the theory that an increase in temperature increases permeate flux resulting in high permeability of membranes and an increase in permeate TDS.

In recent years, high permeate water quality has been expected to be produced from SWRO desalination plants. Permeate water with TDS as low as 200 mg/l or less after re-mineralization is the expected quality (Kim et al., 2020). Optimization of the V & A plant resulted in a permeate TDS of around 82 mg/l (Table 6 and Table 7), which is very desirable. On the other hand, an increase in temperature results in a reduction in SEC and an increase in recovery ratio (Atab et al., 2018).

Figure 8 shows that feed pressure is directly proportional to the quality of product water. This means that as feed pressure increases, permeate TDS generally decreases, leading to improved quality of water produced. This is in agreement with Lee et al., (2015) and Du et al. (2020) who stated that an increase in feed pressure increases permeate flux and salt rejection while at the same time reducing SEC. Gandhidasan and Al-Mojel (2009) also agree that an exponential decrease in permeate TDS was recorded when input pressure was increased. Gude (2011) concluded that pressure increase has a positive impact on several parameters like salt rejection, recovery ratio and energy consumption.

The results in Figure. 9 show that a slight increase in pH led to a decrease in permeate TDS. The product quality improved dramatically with a slight increase in pH. Vaseghi et al. (2016) are in agreement with this phenomenon as they state that pH varies inversely proportional to permeate TDS, where lower ion concentration is achieved when pH increases. However, an increase in feed pH resulted in an increase in permeate TDS for low flow rates, as is recorded by Alahmad (2010). Su et al. reiterate that pH variations generally have no effect on permeate TDS, because with an increase in pH cation rejection decreases while anion rejection increases (Su et al., 2017). Park and Kwon (2018) state that variations in pH have not yet been well understood; salt passage and permeate flux is higher in low and high pH due to membrane swelling.

6. CONCLUSIONS

WAVE simulation and optimization resulted in the theoretical improvement of the plant. Increasing the feed flow rate to about 24 m^3/h on the train resulted in 86 % production capacity, an increase of about 18 % towards achieving the design capacity of the plant. This was necessitated without changing the membranes or recovery ratio of the plant. SEC optimization, which is the chief objective of optimization, also resulted in a 7.3 % improvement in energy consumption, a reduction of about 0.48 kWh/m^3. Feed pressure of the system was also reduced to 50.5 bar from an average of about 55 bar in operation in the plant previously. Reduction in feed pressure led to a reduction in SEC, also leading to a reduction in total running costs of the plant (Appendix B), as compared to the simulated total running costs (Appendix A).

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REFERENCES

1. *Ahmed, F. E., Hashaikeh, R., Diabat, A., & Hilal, N. (2019). Mathematical and optimization modelling in desalination: State-of-the-art and future direction. Desalination, 469, 114092. DOI: https://doi.org/10.1016/j.desal.2019.114092*
2. *Randy Ncube & Freddie L. Inambao, "Experimental Data Analysis for a Reverse Osmosis Desalination Plant",International Journal of Mechanical and Production Engineering Research and Development (IJMPERD),Vol. 11, Issue 3,pp, 421-440*
3. *Alahmad, M. (2010). Prediction of performance of sea water reverse osmosis units. Desalination, 261(1-2), 131-137. DOI: https://doi.org/10.1016/j.desal.2010.05.018*
4. *Randy Ncube & Professor Freddie L. Inambao, "Theoretical Data Analysis for a Small-Scale Reverse Osmosis Desalination Plant",International Journal of Mechanical and Production Engineering Research and Development (IJMPERD),Vol. 11, Issue 2,pp, 31-40*
5. *Altaee, A.. (2012). Computational model for estimating reverse osmosis system design and performance: Part-one binary feed solution. Desalination, 291, 101-105. DOI: https://doi.org/10.1016/j.desal.2012.01.028*
6. *S. R. Kalbande, Priyanka Nayak, Sneha Deshmukh & V. P. Khambalkar, "Thermal Evaluation of Solar Water Desalination System with Evacuated Tubes",International Journal of Applied and Natural Sciences (IJANS),Vol. 6, Issue 1,pp; 41-54*
7. *Ang, W. & Mohammad, A. (2015. Mathematical modeling of membrane operations for water treatment. In A. Basile, A. Cassano, & N. K. Rastogi (Eds.), Advances in membrane technologies for water treatment (pp. 379-407), Woodhead Publishing.*
8. *K. K. Matrawy, "Modeling and Performance Evaluation of an Indirect Solar Desalination System",International Journal of Mechanical Engineering (IJME),Vol. 6, Issue 4,pp; 1-14*

9. *Assad, M. E. H., Al-Shabi, M., & Khaled. F. (2020). Reverse osmosis with an energy recovery device for seawater desalination powered by Geothermal energy. In 2020 Advances in Science and Engineering Technology International Conferences (ASET). pp. 1-5. IEEE.*

10. *Atab, M. S., Smallbone, A., & Roskilly, A. (2016). An operational and economic study of a reverse osmosis desalination system for potable water and land irrigation. Desalination, 397, 174-184. DOI: https://doi.org/10.1016/j.desal.2016.06.020*

11. *Atab, M. S., Smallbone, A., & Roskilly, A. (2018). A hybrid reverse osmosis/adsorption desalination plant for irrigation and drinking water. Desalination, 444, 44-52. DOI: https://doi.org/10.1016/j.desal.2018.07.008*

12. *Djebedjian, B., Gad, H., Khaled, I., & Rayan. M. A. (2008). Optimization of reverse osmosis desalination system using genetic algorithms technique. In Twelfth International Water Technology Conference, IWTC12, Alexandria, Egypt.*

13. *Du, J. R., Zhang, X., Feng, X., Wu, Y., Cheng, F., & Ali, M. E. (2020). Desalination of high salinity brackish water by an NF-RO hybrid system. Desalination, 491, 114445. DOI: https://doi.org/10.1016/j.desal.2020.114445*

14. *DuPont. (2021). WAVE Design Software. Available from: https://www.dupont.com/water/resources/design-software.html*

15. *Edina, M. (2017). New design software integrates three technologies into one tool. Available from: https://corporate.dow.com/en-us/news/press-releases/new-design-software-integrates-three-technologies-into-one-tool.html*

16. *Enqvist, J. P. & Ziervogel, G. (2019). Water governance and justice in Cape Town: An overview. Wiley Interdisciplinary Reviews: Water, 6(4), e1354. DOI: https://doi.org/10.1002/wat2.1354*

17. *Gandhidasan, P. & Al-Mojel, S. A. (2009). Effect of feed pressure on the performance of the photovoltaic powered reverse osmosis seawater desalination system. Renewable Energy, 34(12), 2824-2830. DOI: https://doi.org/10.1016/j.renene.2009.04.029*

18. *Gilabert Oriol, G., Hassan, M., Dewisme, J., Busch, M., & Garcia-Molina, V. (2013). High efficiency operation of pressurized ultrafiltration for seawater desalination based on advanced cleaning research. Industrial & Engineering Chemistry Research, 52(45), 15939-15945. DOI: https://doi.org/10.1021/ie402643z*

19. *Gude, V. G. (2011). Energy consumption and recovery in reverse osmosis. Desalination and Water Treatment, 36(1-3), 239-260. DOI: https://doi.org/10.5004/dwt.2011.2534*

20. *Guler, E., Ozakdag, D., Arda, M., Yuksel, M., & Kabay, N. (2010). Effect of temperature on seawater desalination-water quality analyses for desalinated seawater for its use as drinking and irrigation water. Environmental Geochemistry and Health, 32(4), 335-339. DOI: 10.1007/s10653-010-9294-x.*

21. *Jiang, A., Q. Ding, Q., Wang, J., Jiangzhou, S., Cheng, W., & Xing, C. (2014). Mathematical modeling and simulation of SWRO process based on simultaneous method. Journal of Applied Mathematics, 2014. DOI: http://dx.doi.org/10.1155/2014/908569*

22. *Khalifa, A., Ahmad, H., Antar, M., Laoui, T., & Khayet, M. (2017). Experimental and theoretical investigations on water desalination using direct contact membrane distillation. Desalination, 404, 22-34. DOI: https://doi.org/10.1016/j.desal.2016.10.009*

23. *Kim, S. J., Lee, Y. G., Oh, S., Lee, Y. S., Kim, Y. M., Jeon, M. G., Lee, S., Kim, I. S. & Kim, J. H. Energy saving methodology for the SWRO desalination process: Control of operating temperature and pressure. Desalination, 247(1-3), 260-270. DOI: https://doi.org/10.1016/j.desal.2008.12.006*

24. *Kim, J., Park, K., & Hong, S. (2020). Application of two-stage reverse osmosis system for desalination of high-salinity and high-temperature seawater with improved stability and performance. Desalination, 492, 114645. DOI:*

https://doi.org/10.1016/j.desal.2020.114645

25. Kim, J., Park, K., Yang, D. R., & Hong, S. A comprehensive review of energy consumption of seawater reverse osmosis desalination plants. Applied Energy, 254, 113652. DOI: https://doi.org/10.1016/j.apenergy.2019.113652
26. Kim, S. J., Oh, S., Lee, Y. G., Jeon, M. G., Kim, I. S., & Kim, J. H. (2009). A control methodology for the feed water temperature to optimize SWRO desalination process using genetic programming. Desalination, 247(1-3), 190-199. DOI: https://doi.org/10.1016/j.desal.2008.12.024
27. Koutsou, C., Kritikos, E., Karabelas, A., & Kostoglou, M. (2020). Analysis of temperature effects on the specific energy consumption in reverse osmosis desalination processes. Desalination, 476, 114213. DOI: https://doi.org/10.1016/j.desal.2019.114213
28. Lappalainen, J., Korvola, T., & Alopaeus, V. (2017). Modelling and dynamic simulation of a large MSF plant using local phase equilibrium and simultaneous mass, momentum, and energy solver. Computers & Chemical Engineering, 97, 242-258. DOI: https://doi.org/10.1016/j.compchemeng.2016.11.039
29. Lee, C.-J., Chen, Y.-S., & Wang, G.-B. (2010). A dynamic simulation model of reverse osmosis desalination systems. In The 5th International Symposium on Design, Operation and Control of Chemical Processes, PSE ASIA, Singapore. 2010.
30. Lee, J. J., Woo, Y. C., & Kim, H.-S. (2015). Effect of driving pressure and recovery rate on the performance of nanofiltration and reverse osmosis membranes for the treatment of the effluent from MBR. Desalination and Water Treatment, 54(13), 3589-3595. DOI: https://doi.org/10.1080/19443994.2014.923196
31. Libotean, D., Giralt, J., Giralt, F., Rallo, R., Wolfe, T., & Cohen, Y. (2009). Neural network approach for modeling the performance of reverse osmosis membrane desalting. Journal of Membrane Science, 326(2), 408-419. DOI: https://doi.org/10.1016/j.memsci.2008.10.028
32. Murthy, Z. & Vengal, J. C. (2006). Optimization of a reverse osmosis system using genetic algorithm. Separation Science and Technology, 41(4), 647-663. DOI: 10.1080/01496390500526854
33. Nisan, S., Commercon, B., & Dardour, S. (20050. A new method for the treatment of the reverse osmosis process, with preheating of the feedwater. Desalination, 182(1-3), 483-495. DOI: https://doi.org/10.1016/j.desal.2005.02.041
34. Oh, H.-J., Hwang, T.-M., & Lee, S. (2009). A simplified simulation model of RO systems for seawater desalination. Desalination, 238(1-3), 128-139. DOI: https://doi.org/10.1016/j.desal.2008.01.043
35. Park, H.-G. & Kwon, Y.-N. (2018). Investigation on the factors determining permeate pH in reverse osmosis membrane processes. Desalination, 430, 147-158. DOI: https://doi.org/10.1016/j.desal.2017.12.060
36. Poullikkas, A. (2001). Optimization algorithm for reverse osmosis desalination economics. Desalination, 133(1), 75-81 DOI: https://doi.org/10.1016/S0011-9164(01)00084-4.
37. Sassi, K. M. & Mujtaba, I. M. (2010). Simulation and optimization of full scale reverse osmosis desalination plant.Computer Aided Chemical Engineering, 28, 895-900. DOI: https://doi.org/10.1016/S1570-7946(10)28150-6
38. Sassi, K. M. & Mujtaba, I. M. (2011). Optimal design and operation of reverse osmosis desalination process with membrane fouling. Chemical Engineering Journal, 171(2), 582-593. DOI: https://doi.org/10.1016/j.cej.2011.04.034
39. Su, X., Song, Y., Li, T., & Gao, C. (2017). Effect of feed water characteristics on nanofiltration separating performance for brackish water treatment in the Huanghuai region of China. Journal of Water Process Engineering, 19, 147-155. DOI: https://doi.org/10.1016/j.jwpe.2017.07.021

40. *Swartz, C., Du Plessis, J., Burger, A., & Offringa, G. (2006). A desalination guide for South African municipal engineers. Water SA, 32(5). DOI: 10.4314/wsa.v32i5.47845*

41. *Vaseghi, G., Ghassemi, A., & Loya, J. (2016). Characterization of reverse osmosis and nanofiltration membranes: Effects of operating conditions and specific ion rejection. Desalination and Water Treatment, 57(50), 23461-23472. DOI: https://doi.org/10.1080/19443994.2015.1135825*

42. *Zarai, N., Tadeo, F., & Chaabene, M. (2013). Planning of the operating points in desalination plants based on energy optimization. International Journal of Computer Applications, 68(18), Available from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.403.6874&rep=rep1&type=pdf*

APPENDIX

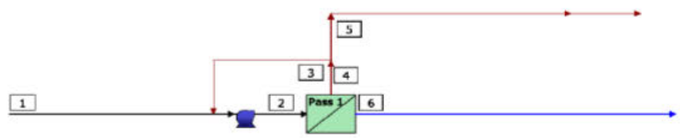
A: 110-10 Train Detailed Simulation Report

DUPONT

WATER APPLICATION VALUE ENGINE
WATER SOLUTIONS

RO Detailed Report

RO System Flow Diagram



#	Description	Flow (m^3/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	64.5	33,619	0.0
2	Net Feed to Pass 1	69.3	34,748	47.0
3	Concentrate Recycle from Pass 1 to Pass 1	4.94	48,753	44.1
4	Total Concentrate from Pass 1	49.4	48,752	44.1
5	Net Concentrate from RO System	44.4	48,752	44.1
6	Net Product from RO System	20.0	104.8	0.0

RO System Overview

Total # of Trains	1	Online =	1	Standby =	0	RO Recovery	31.0 %
System Flow Rate	(m^3/h)	Net Feed =	64.5	Net Product =	20.0		

Pass		Pass 1
Stream Name		Stream 1
Water Type		Sea Water (With conventional pretreatment, SDI < 5)
Number of Elements		42
Total Active Area	(m^2)	1717
Feed Flow per Pass	(m^3/h)	69.3
Feed TDS*	(mg/L)	34,748
Feed Pressure	(bar)	47.0
Flow Factor Per Stage		0.85
Permeate Flow per Pass	(m^3/h)	20.0
Pass Average flux	(LMH)	11.6
Permeate TDS*	(mg/L)	104.8
Pass Recovery		28.9 %
Average NDP	(bar)	14.1
Specific Energy	(kWh/m^3)	5.68
Temperature	(°C)	14.0
pH		7.2
Chemical Dose		-
RO System Recovery		31.0 %
Net RO System Recovery		31.0%

Footnotes:

*Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

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WATER APPLICATION VALUE ENGINE
WATER SOLUTIONS

RO Flow Table (Stage Level) - Pass 1

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow (m^3/h)	Recirc Flow (m^3/h)	Feed Press (bar)	Boost Press (bar)	Conc Flow (m^3/h)	Conc Press (bar)	Press Drop (bar)	Perm Flow (m^3/h)	Avg Flux (LMH)	Perm Press (bar)	Perm TDS (mg/L)
1	SW30XLE-440i	6	7	69.3	4.94	46.7	0.0	49.4	44.1	2.5	20.0	11.6	3.0	104.8

RO Solute Concentrations - Pass 1

Concentrations (mg/L as ion)						
		Adjusted Feed		Concentrate	Permeate	
	Raw Feed	Initial	After Recycle	Stage1	Stage1	Total
NH_4^+	0.00	0.00	0.00	0.00	0.00	0.00
K^+	0.00	0.00	0.00	0.00	0.00	0.00
Na^+	9,928	9,928	10,260	14,394	38.22	38.22
Mg^{+2}	1,654	1,654	1,709	2,400	1.60	1.60
Ca^{+2}	441.0	441.0	455.8	639.9	0.42	0.42
Sr^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
Ba^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
CO_3^{-2}	0.00	0.00	0.00	0.00	0.00	0.00
HCO_3^-	0.00	0.00	0.00	0.00	0.00	0.00
NO_3^-	0.00	0.00	0.00	0.00	0.00	0.00
F^-	0.00	0.00	0.00	0.00	0.00	0.00
Cl^-	18,997	18,997	19,632	27,546	63.70	63.69
Br^{-1}	0.00	0.00	0.00	0.00	0.00	0.00
SO_4^{-2}	2,600	2,600	2,687	3,773	0.90	0.90
PO_4^{-3}	0.00	0.00	0.00	0.00	0.00	0.00
SiO_2	0.00	0.00	0.00	0.00	0.00	0.00
Boron	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00
TDS*	33,619	33,619	34,744	48,752	104.8	104.8
Est. Cond. µS/cm	50,408	50,408	51,883	69,718	223	223
pH	7.2	7.2	7.2	7.3	7.2	7.2

Footnotes:

*Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Design Warnings

None

Special Comments

Product	Special Comments
SW30XLE-440i	Consult your DuPont representative for advice on applications above 95°F (35°C).

RO Flow Table (Element Level) - Pass 1

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DUPONT

WATER APPLICATION VALUE ENGINE
WATER SOLUTIONS

Stage	Element	Element Name	Recovery (%)	Feed Flow (m^3/h)	Feed Press (bar)	Feed TDS (mg/L)	Conc Flow (m^3/h)	Perm Flow (m^3/h)	Perm Flux (LMH)	Perm TDS (mg/L)
1	1	SW30XLE-440i	5.9	11.6	46.7	34,744	10.9	0.69	16.8	63.68
1	2	SW30XLE-440i	5.6	10.9	46.2	36,930	10.3	0.61	14.9	75.40
1	3	SW30XLE-440i	5.2	10.3	45.8	39,116	9.73	0.54	13.1	89.82
1	4	SW30XLE-440i	4.8	9.73	45.4	41,263	9.26	0.47	11.4	107.6
1	5	SW30XLE-440i	4.3	9.26	45.1	43,333	8.86	0.40	9.8	129.7
1	6	SW30XLE-440i	3.9	8.86	44.7	45,290	8.52	0.34	8.4	157.1
1	7	SW30XLE-440i	3.4	8.52	44.4	47,104	8.23	0.29	7.1	191.3

Footnotes:

*Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Solubility Warnings

None

RO Chemical Adjustments

	Pass 1 Feed	RO 1st Pass Conc
pH	7.2	7.3
Langelier Saturation Index	0.00	0.00
Stiff & Davis Stability Index	0.00	0.00
TDS* (mg/l)	33,619	48,752
Ionic Strength (molal)	0.72	1.06
HCO_3^- (mg/L)	0.00	0.00
CO_2 (mg/l)	0.00	0.00
CO_3^{-2} (mg/L)	0.00	0.00
$CaSO_4$ (% saturation)	22.4	35.1
$BaSO_4$ (% saturation)	0.00	0.00
$SrSO_4$ (% saturation)	0.00	0.00
CaF_2 (% saturation)	0.00	0.00
SiO_2 (% saturation)	0.00	0.00
$Mg(OH)_2$ (% saturation)	0.01	0.02

Footnotes:

*Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Utility and Chemical Costs

Service Water

	Flow Rate (m^3/h)	Unit Cost ($/$m^3$)	Hourly Cost ($/h)	Daily Cost ($/d)
Non-Product Feed Water				
Pass 1	44.4	0.1400	6.22	149.29
Total Non-product Feed Water Cost	44.4		6.22	149.29
Waste Water Disposal				
Pass 1	44.4	0.6900	30.66	735.76
Total Waste Water Disposal	44.4		30.66	735.76
Total Service Water Cost				885.05

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DUPONT

WATER APPLICATION VALUE ENGINE
WATER SOLUTIONS

Electricity

Peak Power	(kW)	113.5
Energy	(kWh/d)	2,724
Electricity Unit Cost	($/kWh)	0.0900
Electricity Cost	($/d)	245.2
Specific Energy	(kWh/m³)	5.68

Pump	Flow Rate (m³/h)	Power (kW)	Energy (kWh/d)	Cost ($/d)
Pass 1				
Feed	69.33	113.52	2,724.39	245.20
Pass 1 Total		113.52	2,724.39	245.20
System Total		113.52	2,724.39	245.20

Chemical

Chemical	Unit Cost ($/kg)	Dose (mg/L)	Volume (L/d)	Cost ($/d)
Total Chemical Cost				0.0

Utility and Chemical Cost	($/d)	1,130
Specific Water Cost	($/m³)	2.355

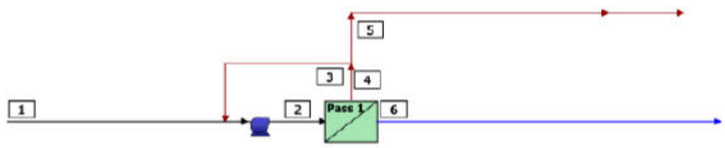
Appendix B: Detailed Optimization Report of the 100-10 Train

DUPONT

WATER APPLICATION VALUE ENGINE
WATER SOLUTIONS

RO Detailed Report

RO System Flow Diagram



#	Description	Flow (m³/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	77.4	33,619	0.0
2	Net Feed to Pass 1	83.2	34,752	50.5
3	Concentrate Recycle from Pass 1 to Pass 1	5.92	48,766	46.9
4	Total Concentrate from Pass 1	59.2	48,767	46.9
5	Net Concentrate from RO System	53.3	48,767	46.9
6	Net Product from RO System	24.0	82.80	0.0

RO System Overview

Total # of Trains	1	Online =	1	Standby =	0	RO Recovery	31.0%
System Flow Rate	(m³/h)	Net Feed =	77.4	Net Product =	24.0		

Pass		Pass 1
Stream Name		Stream 1
Water Type		Sea Water (With conventional pretreatment, SDI < 5)
Number of Elements		42
Total Active Area	(m²)	1717
Feed Flow per Pass	(m³/h)	83.2
Feed TDS*	(mg/L)	34,752
Feed Pressure	(bar)	50.5
Flow Factor Per Stage		0.85
Permeate Flow per Pass	(m³/h)	24.0
Pass Average flux	(LMH)	14.0
Permeate TDS*	(mg/L)	82.80
Pass Recovery		28.8%
Average NDP	(bar)	17.3
Specific Energy	(kWh/m³)	6.10
Temperature	(°C)	13.0
pH		7.3
Chemical Dose		-
RO System Recovery		31.0%
Net RO System Recovery		31.0%

Footnotes:

*Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

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WATER APPLICATION VALUE ENGINE
WATER SOLUTIONS

RO Flow Table (Stage Level) - Pass 1

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow (m^3/h)	Recirc Flow (m^3/h)	Feed Press (bar)	Boost Press (bar)	Conc Flow (m^3/h)	Conc Press (bar)	Press Drop (bar)	Perm Flow (m^3/h)	Avg Flux (LMH)	Perm Press (bar)	Perm TDS (mg/L)
1	SW30XLE-440i	6	7	83.2	5.92	50.2	0.0	59.2	46.9	3.4	24.0	14.0	3.0	82.80

RO Solute Concentrations - Pass 1

Concentrations (mg/L as ion)

		Adjusted Feed		Concentrate	Permeate	
	Raw Feed	Initial	After Recycle	Stage1	Stage1	Total
NH_4^+	0.00	0.00	0.00	0.00	0.00	0.00
K^+	0.00	0.00	0.00	0.00	0.00	0.00
Na^+	9,928	9,928	10,261	14,399	30.18	30.18
Mg^{+2}	1,654	1,654	1,710	2,401	1.27	1.27
Ca^{+2}	441.0	441.0	455.8	640.0	0.33	0.33
Sr^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
Ba^{+2}	0.00	0.00	0.00	0.00	0.00	0.00
CO_3^{-2}	0.00	0.00	0.00	0.00	0.00	0.00
HCO_3^-	0.00	0.00	0.00	0.00	0.00	0.00
NO_3^-	0.00	0.00	0.00	0.00	0.00	0.00
F^-	0.00	0.00	0.00	0.00	0.00	0.00
Cl^-	18,997	18,997	19,635	27,555	50.31	50.31
Br^{-1}	0.00	0.00	0.00	0.00	0.00	0.00
SO_4^{-2}	2,600	2,600	2,687	3,773	0.71	0.71
PO_4^{-3}	0.00	0.00	0.00	0.00	0.00	0.00
SiO_2	0.00	0.00	0.00	0.00	0.00	0.00
Boron	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	0.00	0.00	0.00	0.00	0.00	0.00
TDS[a]	33,619	33,619	34,749	48,767	82.80	82.80
Est. Cond. µS/cm	50,408	50,408	51,889	69,737	177	177
pH	7.3	7.3	7.3	7.3	7.2	7.2

Footnotes:

[a]Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Design Warnings

None

Special Comments

Product	Special Comments
SW30XLE-440i	Consult your DuPont representative for advice on applications above 95°F (35°C).

RO Flow Table (Element Level) - Pass 1

WAVE Version: 1.81.814

Project Name: 100-10 Train Optimization Case: Case 1 Created: 04/05/2021 Page 3 of 5

DUPONT

WATER APPLICATION VALUE ENGINE
WATER SOLUTIONS

Stage	Element	Element Name	Recovery (%)	Feed Flow (m^3/h)	Feed Press (bar)	Feed TDS (mg/L)	Conc Flow (m^3/h)	Perm Flow (m^3/h)	Perm Flux (LMH)	Perm TDS (mg/L)
1	1	SW30XLE-440i	5.7	13.9	50.2	34,749	13.1	0.78	19.2	52.74
1	2	SW30XLE-440i	5.4	13.1	49.6	36,826	12.4	0.71	17.3	61.33
1	3	SW30XLE-440i	5.1	12.4	49.1	38,928	11.7	0.64	15.5	71.67
1	4	SW30XLE-440i	4.8	11.7	48.6	41,026	11.2	0.56	13.8	84.18
1	5	SW30XLE-440i	4.5	11.2	48.1	43,090	10.7	0.50	12.2	99.36
1	6	SW30XLE-440i	4.1	10.7	47.7	45,087	10.2	0.43	10.6	117.9
1	7	SW30XLE-440i	3.7	10.2	47.2	46,988	9.87	0.38	9.2	140.5

Footnotes:

*Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Solubility Warnings

None

RO Chemical Adjustments

	Pass 1 Feed	RO 1st Pass Conc
pH	7.3	7.3
Langelier Saturation Index	0.00	0.00
Stiff & Davis Stability Index	0.00	0.00
TDS* (mg/l)	33,619	48,767
Ionic Strength (molal)	0.72	1.06
HCO_3^- (mg/L)	0.00	0.00
CO_2 (mg/l)	0.00	0.00
CO_3^{-2} (mg/L)	0.00	0.00
$CaSO_4$ (% saturation)	22.4	35.1
$BaSO_4$ (% saturation)	0.00	0.00
$SrSO_4$ (% saturation)	0.00	0.00
CaF_2 (% saturation)	0.00	0.00
SiO_2 (% saturation)	0.00	0.00
$Mg(OH)_2$ (% saturation)	0.01	0.02

Footnotes:

*Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Utility and Chemical Costs

Service Water

	Flow Rate (m^3/h)	Unit Cost ($/$m^3$)	Hourly Cost ($/h)	Daily Cost ($/d)
Non-Product Feed Water				
Pass 1	53.3	0.1400	7.46	179.08
Total Non-product Feed Water Cost	53.3		7.46	179.08
Waste Water Disposal				
Pass 1	53.3	0.6900	36.77	882.60
Total Waste Water Disposal	53.3		36.77	882.60
Total Service Water Cost				1061.68

WAVE Version: 1.81.814

Project Name: 100-10 Train Optimization Case: Case 1 Created: 04/05/2021 Page 4 of 5

DUPONT

WATER APPLICATION VALUE ENGINE
WATER SOLUTIONS

Electricity

Peak Power	(kW)	146.5
Energy	(kWh/d)	3,515
Electricity Unit Cost	($/kWh)	0.0900
Electricity Cost	($/d)	316.4
Specific Energy	(kWh/m³)	5.10

Pump	Flow Rate (m^3/h)	Power (kW)	Energy (kWh/d)	Cost ($/d)
Pass 1				
Feed	83.17	146.46	3,515.09	316.36
Pass 1 Total		146.46	3,515.09	316.36
System Total		146.46	3,515.09	316.36

Chemical

Chemical	Unit Cost ($/kg)	Dose (mg/L)	Volume (L/d)	Cost ($/d)
Total Chemical Cost				0.0

Utility and Chemical Cost	($/d)	1,378
Specific Water Cost	($/m³)	2.393

WAVE Version: 1.81.814

Project Name: 100-10 Train Optimization Case: Case 1 Created: 04/05/2021 Page 5 of 5

CHAPTER 9. Conclusion and Recommendations

Conclusion

The main aim of this thesis was to perform experiments on an already existing plant, extract data, and perform simulations and optimization of the system. The experiments were performed on the Victoria and Alfred (V&A) Waterfront desalination unit, a plant located in Cape Town, along the coast of the Atlantic Ocean. The plant comprises three desalination trains namely the SW100-10, SW500-4 and the SW500-3 trains. The experimental data used was extracted from the SW100-10 train and statistically analyzed using Microsoft Excel in terms of relationships between parameters like feed and permeate total dissolved salts (TDS), temperature, pressure, energy and pH (Chapter 7). The results of objectives 1 and 2 are summarized below:

- The extracted data showed that the plant operated at an average recovery ratio, feed pressure, feed pH and feed temperature of 31 %, 55 bar, 7.2 and 16 ℃ respectively. Other parameters such as permeate TDS and permeate flow were recorded as 490 mg/l and 460 m^3/d (20 m^3/h) respectively.
- The mathematical modeling results showed a general decrease in permeate conductivity and TDS as temperature increased. This follows a general trend evident in the literature as well that when the temperature of water increases there is a subsequent increase in the water permeability coefficient and the salt permeability coefficient of the membrane as well. This increase in temperature leads to a decrease in water viscosity leading to increased permeability of membranes.
- In this study, the graph of permeate TDS and conductivity against pH showed a general decrease in permeate TDS and conductivity as pH increased.
- The relationship between feed TDS and permeate TDS showed a slight decrease in the permeate TDS as feed TDS increased, but research shows that high feed TDS results in membrane surface fouling and scaling thereby reducing the effective area, ultimately reducing the membrane flux leading to an increase in permeate TDS.
- The analysis of results also showed that as pressure was increased, permeate TDS slightly increased. This is so because an increase in feed pressure leads to an increase in the recovery rate, that is, a higher flowrate on the permeate side is observed compared to the

concentrate side. This results in an accumulation of the rejected salts in the membrane surfaces causing surface concentration and mass transfer in the surfaces leading to an increase in concentration polarization and subsequently low permeate quality.

- The energy consumption as a function of temperature graph showed an increase in energy consumption as feed temperature increased. The main reason is that an increase in temperature leads to an increase in recovery rate leading to an increase in mechanical power consumption.
- Lastly, the experimental data plots for feed pressure and feed TDS against energy consumption showed a general increase in energy consumption as the two variables increased. This is because high feed TDS increases energy consumption owing to the high hydraulic pressure required to overcome the high osmotic pressure.

Studies on modeling, simulations and optimization of the plant were performed. Mathematical modeling was assumed to be following the basic principles and equations of mass and transport theory. Simulation and optimization was accomplished using Water Application Value Engine (WAVE) simulation software. WAVE simulation and optimization resulted in the following theoretical improvements of the plant:

- Increasing the feed flow rate from 20 m^3/h to about 24 m^3/h on the train resulted in 86 % production capacity, an increase of about 18 % towards achieving design capacity of the plant. This was necessitated without changing the membranes or recovery ratio of the plant.

- The plant produced an average permeate TDS of 490 mg/l. An increase in feed flow resulted in a theoretical permeate TDS of around 82 mg/l, a positive increase of about 18 % which is very desirable. This also led to a theoretical increase in salt rejection from 98.81 % (experimental data) to 99.76 %, a positive increase of 0.95 %.

- Specific energy consumption (SEC) optimization, which was the main objective of optimization, also resulted in a 7.3 % improvement in energy consumption, a reduction of about 0.48 kWh/m^3. Feed pressure of the system was also reduced to 50.5 bar from an average of about 55 bar after optimization. The V & A plant operated with a SEC of 6.58 kWh/m^3. Increasing the feed flow and reducing feed pressure to about 24 m^3/h and 50.5

bar respectively during the optimization process resulted in a reduction in SEC to 6.10 kWh/m^3, also leading to a reduction in total running costs of the plant.

A comparison of the theoretical modeling and optimization of a RO system using two membrane modeling softwares namely Reverse Osmosis System Analysis (ROSA) for FILMTEC™ membranes (DOW Water and Process Solutions) and Integrated Membrane Solutions Design (IMSDesign) (Hydranautics Nitto Group Company) showed that for a small scale desalination plant, IMSDesign had lower setup cost than that of the ROSA software, although the SEC of the ROSA setup was lower than that of IMSDesign setup. The IMSDesign setup also showed that the required design output of less than 500 mg/l permeate TDS could be obtained.

A comprehensive theoretical data analysis of the SWRO desalination unit, and a statistical analysis of different parameters were carried out to come up with several graphs of correlations. Important RO parameters such as SEC, temperature, feed pressure and permeate TDS were plotted against each other to come up with their graphical correlations. These analyses showed that factors such as feed water flow rate, temperature, salinity, and membrane type, are very important in the monitoring and controlling of the RO system so as to achieve optimal performance. The results showed that energy efficiency could be improved by variation of feed temperature, that is to say, an increase in feed water temperature resulted in the reduction of SEC. It was deduced that the SEC increases as feed pressure increases, and the relationship between temperature and permeate TDS showed that as temperature increased, the permeate TDS also increased. Therefore, to promote the adoption of a more sustainable, cost-effective, and environmentally friendly desalination operation, parameters such as temperature and feed flow rate should be optimized over other parameters.

Recommendations

Since optimization of the system was mainly theoretical, there is a need to implement the above changes in input parameters on a real plant for feasibility studies, comparison of theoretical and practical results, and certification of the results.

One of the greatest limitations of RO is membrane fouling. This includes the process of concentration polarization. Ongoing research to reduce this problem is being undertaken by engineers and membrane design companies. Incorporation of scheduled self-cleaning using machine learning programs in the RO process may be the solution to this problem. This will help in the reduction of membrane fouling and increase the life-span of the membranes. But self-cleaning does not happen on its own, it requires process control and coding of the system. The RO system needs to be installed along with machine learning programs that include self-diagnostics, where each and every component is monitored by a program which will measure the component's working efficiency and report in real-time to the user. Whenever a component exceeds its life cycle, or as a result of wear and tear, does not operate in the required range of operation efficiency, the program will recommend a component check-up or component replacement. This will lead to optimum working conditions for all the components and consequently a reduction in corrective maintenance, thereby improving output while at the same time reducing the costs of operation.

Appendix : Editing, Journal acceptance and Journal publications certificates

This appendix contains certificates of editing by a professional editor for language, layout and references checks for all the published articles and chapters in this thesis. This appendix also includes publications certificates issued by the different publishing houses for the published articles.

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Re: **Randy Ncube**
Journal article: **A REVIEW OF DESALINATION SYSTEMS USING THE REVERSE OSMOSIS TECHNIQUE**

I confirm that I have edited this article and the references for clarity, language and layout. I returned the document to the author with track changes so correct implementation of the changes and clarifications requested in the text and references is the responsibility of the author. I am a freelance editor specialising in proofreading and editing academic documents. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homeopathy at Technikon Natal in 1999 (now the Durban University of Technology). I was a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology for 13 years.

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Re: **Randy Ncube**
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ISSN Print: 0976 - 6340 ISSN Online: 0976 - 6359

Official Acceptance of Research Paper

Paper ID: IJMET/10/09/2019/IJMET_44518 **Date:** 28-Sep-2019

Dear **Randy Ncube and Professor Freddie L. Inambao**

We would like to inform you that your paper titled **"A REVIEW OF DESALINATION SYSTEMS USING THE REVERSE OSMOSIS TECHNIQUE"** has been accepted for publication in **International Journal of Mechanical Engineering and Technology (IJMET),** Volume 10, Issue 09, (September 2019) issue of the journal based on the Recommendation of the Editorial Board without any major corrections in the content submitted by the researcher.

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ISSN Print: 0976 - 6340 ISSN Online: 0976 - 6359

Review Report

Date: 28-September-2019

Title: A REVIEW OF DESALINATION SYSTEMS USING THE REVERSE OSMOSIS TECHNIQUE

Authors: Randy Ncube and Professor Freddie L. Inambao

Evaluation	Poor	Fair	Good	Very Good	Outstanding
Originality					√
Innovation				√	
Technical merit					√
Applicability					√
Presentation and English					√
Match to Journal Topic					√
Recommendation to Chief Editors					
	Strongly Reject	Reject	Marginally Accept	Accept	Strongly Accept
Recommendation					√

Review Comments: This paper Water is and has always been the source of life for humans, animals and every other living organism, but its availability is slowly diminishing by the day. Scarcity of potable and fresh water is a major concern the world over, especially in the Middle East and Africa. There is a need for new, energy efficient and eco-friendly ways of producing fresh water from the vast and abundant sources of saline and brackish water available. The main objective of this paper is to review current and already developed RO desalination methods, membranes and the mathematical modelling and optimization of RO systems using Genetic Algorithm. **Development study. Paper Accepted for publication in IJMET.**

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Official Acceptance of Research Paper

Paper ID: IJMET/10/11/2019/IJMET_44877 **Date:** 25-Nov-2019

Dear **Randy Ncube and Professor Freddie L. Inambao**

We would like to inform you that your paper titled **"SEA WATER REVERSE OSMOSIS DESALINATION: ENERGY AND ECONOMIC ANALYSIS"** has been accepted for publication in **International Journal of Mechanical Engineering and Technology (IJMET),** Volume 10, Issue 11, (November 2019) issue of the journal based on the Recommendation of the Editorial Board without any major corrections in the content submitted by the researcher.

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ISSN Print: 0976 - 6340 ISSN Online: 0976 - 6359

Review Report

Date: 25-November-2019

Title: SEA WATER REVERSE OSMOSIS DESALINATION: ENERGY AND ECONOMIC ANALYSIS

Authors: Randy Ncube and Professor Freddie L. Inambao

Evaluation	Poor	Fair	Good	Very Good	Outstanding
Originality					√
Innovation				√	
Technical merit					√
Applicability					√
Presentation and English					√
Match to Journal Topic					√
Recommendation to Chief Editors					
	Strongly Reject	Reject	Marginally Accept	Accept	Strongly Accept
Recommendation					√

Review Comments: In this paper seeks to analyze the effects of energy and costs of RO desalination technology. Sea water desalination is a process that separates saline water into two major components, the low dissolved salts concentration water stream and the high dissolved salts concentration water, using several generally high energy and cost mechanisms. Research and development of energy and cost effective desalination technologies is an ongoing process as sources of fresh water continue to diminish at an alarming rate while at the same time the population growth is increasing dramatically. In this regard, RO has become the most viable technology in desalination. **Analytical study. Paper Accepted for publication in IJMET.**

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Review Report

Date: 16-March-2020

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Authors: Randy Ncube and Professor Freddie L. Inambao

Evaluation	Poor	Fair	Good	Very Good	Outstanding
Originality					√
Innovation				√	
Technical merit					√
Applicability					√
Presentation and English					√
Match to Journal Topic					√
Recommendation to Chief Editors					
	Strongly Reject	Reject	Marginally Accept	Accept	Strongly Accept
Recommendation					√

Review Comments: In this paper modeling and optimization of reverse osmosis (RO) desalination plants is ongoing in order to come up with sustainable and efficient RO plants. Several techniques have been employed to come up with mathematical models of mass and heat transfer, salt rejection and membrane solute permeability, including genetic algorithms (GA) and neural networks techniques. Incorporation of PID controllers have been well known and widely used to improve the dynamic response as well as to reduce or eliminate the steady state errors and improve responses. **Analytical study.** **Paper Accepted for publication in IJMET.**

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Ref. No.: 19900 Dated: 29/10/2020

Dear Dr. Freddie Inambao,

Paper Code: 19900-IJERT

We are very pleased to inform you that your paper "MEMBRANE MODELING AND SIMULATION FOR A SMALL SCALE REVERSE OSMOSIS DESALINATION PLANT ", is accepted by our Editor-in-chief for our journal, International Journal of Engineering Research and Technology (IJERT) ISSN 09743154, scopus indexed (active - 2020).
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Thanking you and looking forward to hear you soon,
With warm regards,

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Paper Id: IJMPERDAPR20214 Date: 03/08/2021

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