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Design Analysis of Fresh Water Production System Using the Reverse Osmosis Method

EMEKA ONYEUKWU[1], OSILEM CHIBUZOR[2]
[1, 2]Department of Marine and Offshore Engineering, Faculty of Engineering, Rivers State University, Port-Harcourt, Rivers State, Nigeria

Abstract- The need for fresh water on board a ship or offshore structure for passengers, crew, machinery and auxiliary uses has led to the high demand for fresh water. A cruise ship has the highest fresh water requirement compared with other ship types and as such the option of depending on natural source of water (rain) or collection from port is completely not feasible; accordingly, the production of fresh water on the ship is the only possible and convenient source. The fresh water requirement is determined considering the number of passengers, crew and other fresh water dependent machineries and auxiliary systems. The Reverse Osmosis process is chosen to be used for the fresh water production on the cruise ship, with membrane element selection done considering the element specification in relation to the expected fresh water production. The high pressure pump is selected to satisfy the feed flow rate required to produce the expected fresh water. Pre-treatment is carried out before the reverse osmosis process to remove solid particles and impurities, and post-treatment is done after the reverse osmosis process to improve fresh water quality. The membrane performance is calculated and results tabulated and discussed. The effect of changes in some parameters on the membrane performance is discussed and recommendations given.

Index Terms- Fresh Water Production, Reverse Osmosis, Desalination, Membrane Performance, Cruise Ship, Seawater Treatment.

I. INTRODUCTION

1.1 Background to the Study

There are some important systems on a ship without which the ship cannot be said to be in perfect condition suitable for both the crew members and the passengers. Water is very essential to life and its unavailability makes the existence of plants, animals and man impossible. Man does not need water only for survival but for industrial and household purposes. Water covers approximately 71% of our planet and one would think our needs would be met, but the problem therefore is not the availability of water but the availability of portable fresh water, as not all water is suitable for human and industrial use. Drinking contaminated water can be detrimental to human health, causing cholera, dehydration, central nervous system problems, etc. Only 3% of the water present on earth is fresh water and the majority of the rest is salt water. The water may have harmful compounds or the salinity may be too high. Also, people are mobile, necessitating the need to have sources of fresh portable water available, such as on ships that travel on the ocean for months.

Table 1: Difference between Salt Water and Fresh Water

S/no	FRESH WATER	SEA WATER
1.	It has a density of 1.000 kg/l	It has a density of about 1.025 kg/l
2.	It is most suitable for human consumption	It is not suitable for human consumption
3.	Accounts for 2.5–2.75% of all earth's water	Accounts for 97% of all earth's water
4.	It contains less than 0.05% of salt	It contains about 3.5% of salt

From Table 1, it can be seen that the chemical composition difference between fresh water and sea water makes the former more suitable for human consumption and domestic use, while the latter is more abundant on earth.

1.2 Aim and Objectives of the Study

The aim of this research work is to design a fresh water production system on a cruise ship for several uses such as domestic, engine cooling and other hotel services.

The objectives of this project work included to design an excellent fresh water production system on a cruise ship, to design a fresh water production system that will be suitable for human consumption and several other uses and to reduce the energy consumption of the Reverse Osmosis system by making use of an energy recovery device.

1.3 Statement of the Problem

Basically, most people imagine the possibility of onboard fresh water production as a complex and very expensive project and as such prefer the alternative of getting fresh water from port. This assumption has led to many spending more time on the sea and going through many unwanted routes to access a port for fresh water intake, as the amount of fresh water required on a cruise ship makes it impossible for the fresh water taken into the ship at the port of departure to be sufficient for the duration of the voyage. Also, most water treatment and distribution systems use metallic and galvanized pipes, which are subject to rust, thus causing health problems like typhoid fever among passengers and crew members. This project seeks to tackle such problems and proffer solutions on a better way to produce fresh water on a cruise ship that is safe, less expensive and more efficient.

1.4 Scope of the Study

The scope of the research work is to provide the reader with an apt knowledge of the facts about water, its importance to the body, the difference between fresh water and salt water, the various sources of fresh water on a ship, the various means of fresh water production on a ship. It also covers the design calculations of the reverse osmosis (RO) fresh water production.

II. LITERATURE REVIEW

2.1 Review of Literature

The process known as osmosis has been happening in nature for millions of years, but from a scientific standpoint it was first discovered back in 1748 by Jean-Antoine Nollet, a French clergyman and physicist. Nollet was able to replicate the osmotic process by using a pig's bladder as a membrane to show that solvent molecules from low solute water could flow through the bladder wall into a higher solute concentration made of alcohol. He proved that a solvent could pass selectively through a semi-permeable membrane through the process of natural osmotic pressure, and the solvent will continually enter through the cell membrane until dynamic equilibrium is reached on both sides of the bladder.

Tang and Chen (2002) focused on the production of a large amount of wastewater that is highly coloured with high loading of inorganic salt. Crossflow nanofiltration using thin film composite polysulfone membrane was used to recover the electrolyte solution and reject the colour. Using a synthetic textile effluent of reactive dye and NaCl solution, the study dealt with the mechanism controlling flux and rejection by varying four main parameters: cross flow velocity, initial dye concentration, feed pressure, and electrolyte concentration. The results showed that flux was dominated by the osmotic pressure, created from the presence of NaCl, and that dye concentration did not significantly affect the flux or rejection. Working at low pressures of up to 500 kPa, relatively high fluxes were obtained, with an average dye rejection of 98% and NaCl rejections of less than 14%. Thus, a high quality of reusable water could be recovered. This paper sets out to characterize the structural behaviour of a Cork composite hullform of a deep-U Catamaran vessel (DUC) based on the conventional longitudinal shear force and bending moment theory and Henky's von-Mises Stress criteria. It considered the longitudinal Still-water and Maximum Global wave induced loads on the vessel (Chuku et al., 2024).

Jian-Jun Qin et al. (2005) arrived at the relationship between feed pH and permeate pH in the reverse osmosis (RO) process, which was investigated in a pH range of 1.6–7.0 when town water was used as feed. Three types of flat-sheet RO membranes with varying isoelectric points in a pH range of 3.2–6.5 were tested in the laboratory. The experimental results showed that for each RO membrane tested, there was a critical feed pH, below which RO permeate pH was higher than feed pH, but above which RO permeate pH was lower than feed pH. The critical feed pH for all membranes was 4.4–4.5, which was independent of the isoelectric point of the RO membrane used. It was found that the existence of HCO_3^- in the feed and its transmission in the RO process may have played a key role on the critical feed pH, and the co-existing divalent ions had an influence on reducing the rejections of monovalent ions. When running at low speed inside or below 12 knots, it is evident that the EDDI for all of the vessels was improved due to their short length, breadth, draft, and prismatic coefficient (Chuku et al., 2024).

Gomez (2007) discussed a case study in one of the textile units on upgradation of a full-scale effluent treatment plant comprising chemical, biological, tertiary and advanced treatment processes. This paper demonstrates the investigation on the hydrodynamic performance of the initial and optimised hull form of a parent ship from the resistance, power and sea keeping point of view. Based on the analytical results, it was noted that the resistance results of the optimised hull are lower than the initial hull at different speeds under the same conditions (Mac-Pepple, 2021).

2.2 Definition of Terms

2.2.1 Osmosis

This is the spontaneous flow of water from a less concentrated solution to a more concentrated solution through a semi-permeable membrane until energy equilibrium is achieved.

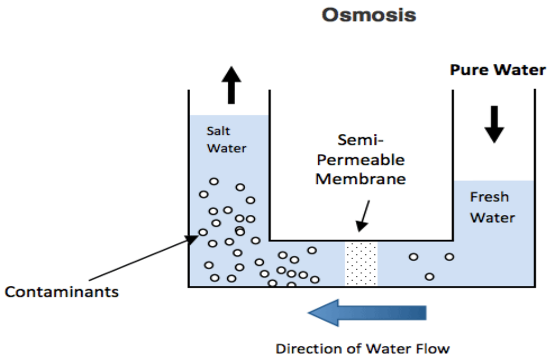

Figure 1: Osmosis System

2.2.2 Reverse Osmosis

This is a water purification technology that uses a semi-permeable membrane that allows the fluid that is being purified to pass through it while removing ions, contaminants, molecules and larger particles from drinking water.

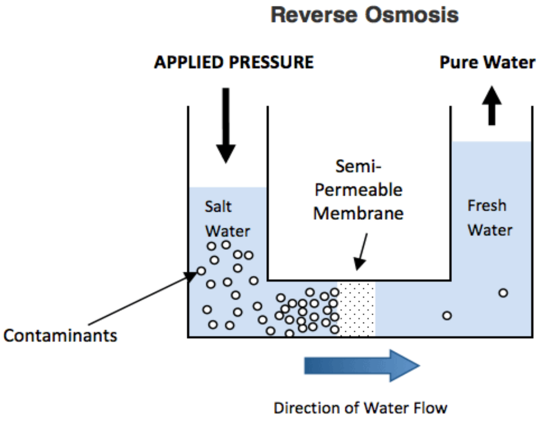

Figure 2: Reverse Osmosis System

2.2.3 Osmotic Pressure

This is the driving force of the reverse osmosis process. It is used to raise the chemical potential of the water in the salt solution and cause solvent flow to the pure water side. The osmotic pressure is a solution property proportional to the salt concentration and independent of the membrane. The RO feed pump has to generate sufficient pressure to overcome this osmotic pressure before permeate is produced. These findings contribute directly to improved maritime safety, operational guidelines, and vessel design standards (Chuku *et al.,* 2025).

2.2.4 Feed Pump

This is the input solution which enters the treatment/purification system and is pressurized (as in Reverse Osmosis), including the raw water supply prior to the treatment.

2.3 Sources of Fresh Water

There are several sources of fresh water on a ship which includes natural source (rain), collection from ports and desalination.

2.4 Uses of Fresh Water

Fresh potable water is used in various ways on board ships, including direct human consumption, food preparation and sanitation/hygiene activities. Potential use includes preparation of hot and cold beverages, such as coffee, tea and powdered beverages, ice cubes in drinks, and reconstitution of dehydrated foods, such as soups, noodles and infant formula, food washing and preparation, direct ingestion from cold-water taps and water fountains, reconstitution and/or ingestion of medications, brushing of teeth, hand and face washing, bathing and showering, dishwashing, cleaning of utensils and work areas, laundering purposes (could potentially use a lower grade of water) and emergency medical use.

Although some uses do not necessitate consumption, they involve human contact and possibly incidental ingestion (e.g. tooth brushing). All non-potable water taps need to be labelled with words such as "UNFIT FOR DRINKING".

2.5 Methods of Desalination

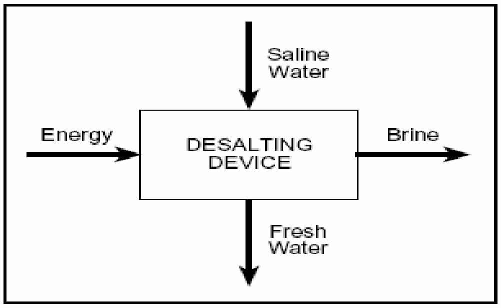

Figure 3: Method of Desalination

There are various desalination processes, classified mainly as follows:

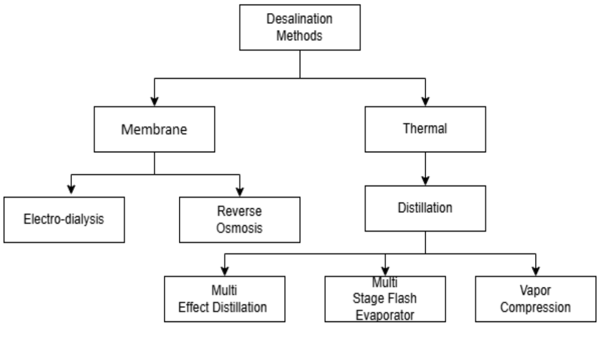

Figure 4: Desalination Processes

2.5.1 Electro Dialysis

Electro-dialysis (ED) employs specially prepared membranes which are semi-permeable to ions based on their charge, and employ electrical current to reduce the ionic content of water. The electro-dialysis membrane process takes advantage of the fact that salt, when dissolved in water, is present in the form of negatively charged ions. An electro-dialysis unit as utilized for desalination consists of a sandwich-type arrangement of alternating cation and anion permeable membranes. Upon the application of an electric charge, the positively charged ions such as sodium pass through the cation-permeable membranes and the negatively charged chlorine moves in the opposite direction and passes through the anion-permeable membranes. The water in the centre of the chamber of each membrane sandwich is thus depleted of salt, while the water passing through intervening pairs of membranes is enriched.

The amount of electric current required in the unit is directly proportional to the amount of salt to be removed, and so the cost of the process depends on the concentration of salt in the feed water, making it economically expensive. However, it also identifies limitations in energy storage capacity and suggests further exploration of advanced battery technologies and renewable energy sources. The findings underscore the importance of hybrid systems in advancing sustainable maritime practices while reducing operational costs and emissions (Robinson & Chuku, 2024).

2.5.2 Reverse Osmosis

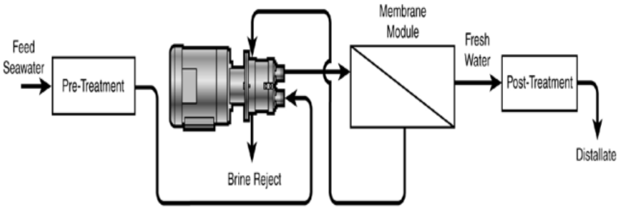

Figure 5: Reverse Osmosis Process

The process of reverse osmosis (RO) represents the finest level of liquid filtration available today. While ordinary liquid filters use a screen to separate particles from water streams, an RO system employs a semi-permeable membrane that separates an extremely high percentage of unwanted molecules.

This is a water purification technology that uses a semi-permeable membrane that allows the fluid that is being purified to pass through it while removing ions, contaminants, molecules and larger particles from drinking water. Most reverse osmosis technology uses a process known as cross flow to allow the membrane to continually clean itself. It is used to purify water and remove salts and other impurities in order to improve the colour, taste or properties of the fluid. It can be used to purify fluids such as glycol and ethanol which will pass through the reverse osmosis membrane while rejecting other ions and contaminants from passing. The most common use for reverse osmosis is in water purification. The process of reverse osmosis requires a driving force to push the fluid through the membrane, and the most common force is pressure from a pump. The higher the pressure, the larger the driving force; subsequently, as the concentration of the fluid being rejected increases, the driving force required to push the fluid through the membrane increases also.

2.6 Reverse Osmosis Process

The Sea Water Reverse Osmosis (SWRO) desalination process comprises the following stages:

2.6.1 Raw Water Supply

Seawater is the raw material for this desalination process. The seawater is taken through sea chests at the bow of the vessel and passes through a metal screen. The seawater supply pumps elevate the pressure of the seawater sufficiently to pass it through the pretreatment process.

2.6.2 Pretreatment — Raw Water Treatment and Conditioning, Fine Filtration

In the pretreatment process, suspended solids that cause fouling of the RO membranes are removed by inline coagulation and filtration. A coagulant is added to the acidified seawater, effectively mixing, and then immediately passing through a dual media filter to remove microflocs that have formed. A disinfectant is injected intermittently into the seawater to prevent microbiological activities in pipes and filters. Acid is required to prevent carbonate scaling on the RO membranes and is also added upstream of the dual media filter.

2.6.3 Reverse Osmosis Process

The feed water is pumped through the membranes with sufficient pressure, with about 40% of the feed water being converted into permeate and the remaining as concentrate. The concentrate passes through the energy recovery process and then is partially transferred to backwash tanks and mainly discharged overboard; the energy consumption is cut by about 35%.

Chemical cleaning of the RO racks will be performed regularly in order to re-establish the initial plant performance.

2.6.4 Permeate Post-treatment

Disinfectant and lime are added downstream of the permeate tank for disinfection, pH adjustment and mineral addition. After adding lime and disinfectant, permeate becomes potable water and is thus pumped to the reservoir tank for distribution.

About 2,000 m^3 storage capacity of permeate tanks shall be provided to allow fluctuations in the potable water supply to be compensated.

III. MATERIALS AND METHODS

3.1 Design Premises

The basic features and design parameters of the desalination unit are as follows:

- Desalination plant of Sea Water Reverse Osmosis (SWRO) technology with a capacity of 400,000 liters/day.
- Desalination water quality as per International Standard.
- Water inlet at the bow of the vessel.
- Brine outlet at the rear end of the vessel and opposite side to the intake.
- Process units are to be located below deck as much as possible.
- Daily fresh water production.
- The result will be validated using MS Excel and C++.

3.2 Ship General Characteristics

Type: Cruise Ship

Tonnage: 135,000 GT

Displacement: 67,000 tonnes

Length: 1,050 ft (318 m)

Beam: 125 ft (38 m) waterline; 130 ft (40 m) extreme

Height: 230 ft (70 m)

Draught: 30 ft (9 m)

Depth: 65 ft (20 m)

Decks: 12 passenger, 16 total

Installed Power: 4 × 12,600 KW (16,900 mhp) Wärtsilä 12V 46D; 2 × 18,000 KW (24,000 mhp) Wärtsilä 16V 46D

Propulsion: 3 × 20 MW (25,000 hp) ABB Azipod all-azimuthing

Speed: 24 knots (44 km/h, 27.5 mph) maximum; 20 knots (36.5 km/h, 23 mph) cruising

Capacity: 2,300 passengers

Crew: 700 officers and crew

3.3 Membrane Parameters

Feed Pressure: 80 bar

Permeate Pressure: 1.01 bar

Concentrate Pressure: 77 bar

Feed Conductivity: 224 µs

Permeate Conductivity: 4.60 µs

Concentrate Conductivity: 320 µs

Feed Flow: 1,000 m^3/d

Temperature: 25°C

3.4 Power/Energy Capacity

High pressure boost pump: 120 KW

Pressure exchanger: 50 KW

3.5 Determination of Fresh Water Requirement

The quantity of fresh water needed on board a cruise ship is not such as can be determined without considering several factors that contribute to the use of fresh water on a voyage. These factors are: the size of the vessel, the type of engines on board the vessel (i.e. diesel or steam), the number of crew (persons) on board, and the voyage distance or time. As a result of the high number of passengers and crew onboard a cruise ship, the amount of fresh water required is very high when compared to other ship types. The table below shows empirical quantities of fresh water needed in some parts of the world.

Table 2: Quantity of Fresh Water Consumption per Person per Day in Liters at Different Parts of the World

World Region/Area	Consumption (US gallon/person/day)	Consumption (liter/person/day)
USA	100	380
Europe	50	190
Africa	40	150
UN Recommended	15	60
Minimum	13	50

From the above table, noting that the cruise ship is to operate in the African region, the fresh water production system will be designed using the following data as guidelines:

- The total number of persons designed to be in the cruise ship is 3,500 persons (2,300 passengers and 700 crew members).
- Each person is assumed to consume 150 liters per day (40 US gallons per day).
- The ship is propelled by diesel engine which will be directly cooled by fresh water.
- The fresh water production system will be designed per day.

3.6 Feed Water Test

The sample of the feed water is obtained and tests carried out to ascertain its chemical composition and thermodynamic properties. The achievable water recovery in a reverse osmosis system depends on the concentration of salts present in the feed water and their tendency to precipitate on the membrane surface, and hence form scaling compounds. The primary goal of this design is to achieve water that has less chemical composition that meets WHO standards for drinking water and other uses. From the test of the water sample carried out, the salinity of the sea water is 36,000 ppm. Below is a table of the chemical composition of the sea water sample.

Table 3: Typical Composition of Seawater with Salinity of 36,000 ppm

Compound	Composition	Mass Percent	PPM
Chlorine	Cl^-	55.03	19,810.8
Sodium	Na^+	30.61	11,019.6
Sulphate	$(SO_4)^{2-}$	7.68	2,764.8
Magnesium	Mg^{2+}	3.69	1,328.4
Calcium	Ca^{2+}	1.16	417.6
Potassium	K^+	1.156	403.2
Carbonic acid	$(CO_3)^-$	0.41	147.6
Bromine	Br^-	0.19	68.4
Boric acid	$H_3BO_3^-$	0.07	25.2
Strontium	Sr^{2+}	0.004	14.4
Total		100	36,000

The thermodynamic properties of the feed water are also obtained from the tests carried out, as they will aid understanding of the differences between the feed water thermodynamic properties and the fresh water thermodynamic properties.

Table 4: Thermodynamic Properties of Seawater and Fresh Water @ 25°C

Thermodynamic Property	Seawater (Salinity = 36,000 ppm)	Fresh Water (Salinity = 0 ppm)
Density [kg/m³]	1,024	997.0
Specific heat [kJ/kg°C]	3.99543	4.186172
Viscosity [kg/ms]	0.960499	0.891807
Thermal conductivity [W/m°C]	0.608656	0.610584

3.7 Pretreatment

In reverse osmosis systems, pretreatment of sea water is very important for the membranes. Therefore, in the pretreatment stage micro-organisms must be destroyed and suspended solids must be removed so that micro-organism growth and salt precipitation does not occur on the membranes. In the pretreatment process, suspended solids that cause fouling of the RO membranes are removed by inline coagulation and filtration. A coagulant is added to the acidified seawater, effectively mixing, and then immediately passing through a dual media filter to remove microflocs that have formed. A disinfectant is injected intermittently into the seawater to prevent microbiological activities in pipes and filters. Acid is required to prevent carbonate scaling on the RO membranes and is also added upstream of the dual media filter.

3.8 Membrane Element Selection

There are different types of membrane element used to treat water from several sources, ranging from tap water, seawater, wastewater, brackish water, etc. The selection of the right membrane element is key to the effective design of the fresh water production system, as the performance of a membrane is specified and compared based on its rate of water production (permeability) and its percent of total salt rejection. The selection of the membrane in this project is based on the water production rate and the salt rejection percentage at low feed pump pressure. Below is a table of some membrane elements used for sea water desalination.

Table 5: Membrane Element Properties

Element	Area (ft²)	Feed Con TDS	Flow GPD	Reject %	Spacer Mil	TCF	NDP Psi	Dia. (in)	Length (in)	Size (in × in)
SWC4 MAX	440	32000	7200	99.8	28	2700	413.5	8	40	8×40

Element	Area (ft²)	Feed Con TDS	Flow GPD	Reject %	Spacer Mil	TCF	NDP Psi	Dia. (in)	Length (in)	Size (in × in)
SWC4-1640	1700	32000	26000	99.8	28	2700	413.5	16	40	16×40
SWC4-LD	400	32000	6500	99.8	34	2700	413.5	8	40	8×40
SWC4B-LD	400	32000	5800	99.8	34	2700	413.5	8	40	8×40
SWC4B MAX	440	32000	6400	99.8	28	2700	413.5	8	40	8×40
SWC5 MAX	440	32000	9900	99.8	28	2700	413.5	8	40	8×40
SWC5-LD	400	32000	9000	99.8	34	2700	413.5	8	40	8×40
SWC5-1640	1700	32000	36000	99.8	28	2700	413.5	16	40	16×40

From the above table, the SWC4-1640 membrane element will be used.

3.9 Design Calculations

3.9.1 Flow Calculations

Permeate Flow Rate (Qp)

$$Q_p = Recovery(\%) \times Q_f \tag{1}$$

Brine Flow Rate (Qb)

$$Q_b = Q_f - Q_p \tag{2}$$

3.9.2 Membrane Performance Calculations

Recovery (%):

This is the amount of water that is being 'recovered' as good permeate water, or the amount of water that is not sent to drain as concentrate but rather collected as permeate.

$$Recovery(\%) = \left(\frac{Q_p}{Q_f}\right) \times 100 \tag{3}$$

Where Q_p = Permeate Flow Rate; Q_f = Feed Flow Rate

Concentration Factor:

This is the degree to which the reverse osmosis feed water dissolved solids are concentrated in the brine.

$$CF = \frac{1}{1 - Recovery} \tag{4}$$

Salt Rejection (%):
This describes the quantity of salt removed from the feed water stream by the reverse osmosis membrane.

$$Salt\ Rejection\ (\%) = \left(1 - \frac{Cp}{cf}\right) \times 100 \tag{5}$$

Where: Cf = Feed Conductivity = 224 µs; Cp = Permeate Conductivity = 4.60 µs

Salt Passage (%):

This describes the quantity of salt which passes through the reverse osmosis membrane into the permeate stream.

$$Salt\ Passage\ (\%) = 100 - Salt\ Rejection\ (\%) \tag{6}$$

Osmotic Pressure (Posm):

This is the minimum pressure which needs to be overcome by the feed pressure entering the membrane element for water to pass through it, or the minimum pressure which needs to be applied to a solution to prevent the inward flow of water across a semi-permeable membrane.

$$Posm = R \times T \times \Sigma mi \tag{7}$$

Where: R = universal gas constant = 8.314 kPa·m³/kgmol·K; T = temperature = 25°C = 298 K; Σmi = concentration of all constituents in the solution = 1.1043 kg·mol/m³

Permeate Flux:

This is the volume of water flowing through the membrane per unit area per unit time.

$$PFl = \frac{NMp}{Ma} \quad (8)$$

Where: NMp = Nominal membrane production = 26,000 gpd; Ma = Membrane area = 1,700 ft²

Number of Membrane Elements Required:

$$N = \frac{Qp}{PFl \times Ma} \quad (9)$$

Where: Qp = desired permeate production; PFl = permeate flux; Ma = membrane area

Pressure Drop (Dp):

The difference between the feed and concentration pressure during water flow through one or more reverse osmosis membrane elements.

$$Dp = a \times \left(\frac{Q_f + Q_c}{2}\right)^b \quad (10)$$

Where: Q_f = feed flow rate = 1,000 m³/d (16.67 m³/h); Q_c = concentrate flow rate = 600 m³/d (10 m³/h); a = coefficient specific for feed spacer = 0.8 mm; b = coefficient specific for element spacer = 0.7112 mm

3.9.3 Head Loss Due to Friction on Permeate Pipe (Hfp)

$$H_{f_p} = \frac{8 f L_p {Q_p}^2}{g \pi^2 {D_p}^5} \quad (11)$$

Where: f = friction factor = 0.012; Lp = length of permeate pipe = 1.016 m; Qp = permeate flow rate = 0.00463 m³/s; g = gravitational acceleration = 9.81 m/s²; π = 3.142; Dp = diameter of permeate pipe = 0.4064 m

3.9.4 Power Calculations

Feed Power Consumption (Pf):

The power that will be consumed by the feed flow into the membrane.

$$P_f = \frac{F_p \times Q_f}{36} \quad (12)$$

Where: F_p = feed pressure = 80 bar; Q_f = feed flow rate = 41.67 m³/h

Concentrate Available Power (ConP):
The power that can be recovered from the brine flow.

$$ConP = \frac{B_p \times Q_b}{36} \quad (13)$$

Where: B_p = brine pressure = 77 bar; Q_b = brine flow rate = 25 m³/h

Specific Energy Consumption (SEC) without Energy Recovery Device (ERD):

$$SEC = \frac{P_{HPP} \times 24}{Q_p} \quad (14)$$

Where: P_{HPP} = high pressure pump power (KW); Q_p = permeate flow rate (m³/h)

Specific Energy Consumption (SEC) with Energy Recovery Device (ERD):

$$SEC = \frac{(P_{HPP} - ER) \times 24}{Q_p} \quad (15)$$

Where: P_{HPP} = high pressure pump power (KW); ER = energy recovered (KW); Q_p = permeate flow rate (m³/h)

Energy Recovered (%):

$$\text{Energy Recovered } (\%) = \frac{\text{SEC with energy recovered}}{\text{SEC without energy recovered}} \times 100 \quad (16)$$

IV. RESULTS AND DISCUSSION

4.1 Results

This section presents result analysis and discussion. The membrane element performance and effects will be determined. The Excel software was used for result effect presentation while the C++ software was used for validation. From the calculations, the following results are obtained.

Table 6: Flow Rate

Calculated Parameter	Dimension	Results
Permeate flow rate	m^3/d	400
Brine flow rate	m^3/d	600

Table 7: Membrane Performance

Calculated Parameters	Dimension	Result
Recovery	%	40
Concentration factor	—	1.667
Salt rejection	%	98
Salt passage	%	2
Osmotic pressure	Bar	27.36
Permeate flux	GFD	15.3
Number of membrane elements required	—	4
Pressure drop	Bar	8.264
Head loss due to friction	m	0.011266
Feed power consumption	KW	92.6
Concentrate available power	KW	53.47
Specific energy consumption without energy recovery	KW/h	69.1
Specific energy consumption with energy recovery	KW/h	40.5

The permeate water produced was tested to have the following constituents:

Table 8: Permeate Water Composition

Compounds	Contents (mg/L)
Total Dissolved Solids TDS	<500
Cl^-	350
SO_2^{2+}	220
Ca^{2+}	90
Mg^{2+}	45
NO_3^-	<50
Cu^{2+}	0.07
Fe^{2+}	0.20
NaCl	250
pH	7.0

4.2 Effects of Different Parameters on Membrane Performance

4.2.1 Primary Factors Affecting Membrane Performance

In general, and due to the complex nature of reverse osmosis membrane properties, membrane performance (both water recovery and salt rejection) can be influenced by various operating parameters within the system: feed pressure and feed water concentration, temperature, and pH. In practice, there is normally an overlap of effects coming from more than one variable since many of the operating parameters are interrelated. However, the degree to which membrane performance could be affected varies significantly, and this depends on which of the various operating parameters manifest significant impact on membrane properties, as well as which of the system's operating conditions are regarded as favourable.

4.2.1.1 Feed Pressure

Feed pressure is one of the major operating parameters that affect the economics of desalination. For given conditions of feed water composition and temperature, feed pressure is directly related to the water recovery rate in the process. Higher recovery rates would require a relatively higher feed pressure at which the system has to operate. Increased feed water pressure also results in increased salt rejection, but the relationship is less evident than in the case of water recovery. As feed water pressure is increased, salt passage becomes less significant since water molecules move through the membrane at a faster rate than the salt molecules are transported. Hence, as feed pressure increases, both water recovery and salt rejection increase. However, at a certain pressure level, salt rejection no longer increases since salt passage remains coupled with water flowing through the membrane. In other words, there is an upper limit to the amount of salt that can be excluded via increasing feed water pressure, and thus an increase in water recovery is more significant than an increase in solute rejection under higher pressure conditions.

4.2.1.2 Feed Water Concentration

The maximum achievable water recovery in a reverse osmosis system not only depends on limiting pressure conditions, but also on the concentration of salts present in the feed water and their tendency to precipitate on the membrane surface, and hence form scaling compounds, as their concentrations increase while permeate is being separated from the feed. Thus, there is a limit to how much frequently-present scale-forming compounds, such as calcium carbonate, magnesium carbonate, calcium sulphate and strontium sulphate, could be concentrated without exceeding their respective solubility limits. Scaling symptoms are mostly prominent, but not solely limited to, the very last stages of a SWRO network due to being subjected to the highest concentration of dissolved salts within the system. Hence, controlling scaling within a reverse osmosis plant is critical to enable successful operation of the process by minimising membrane damage. Many chemical treatment options are available; for instance, the use of sulphuric acid to reduce and control the pH of the system has been the traditional way of preventing calcium carbonate scaling. However, since sulphuric acid is quite hazardous and increases the sulphate content of the water, other alternatives are generally employed, such as the use of scale-inhibiting compounds known as antiscalants.

4.2.1.3 Temperature

Water recovery and salt rejection are very sensitive to changes in feed water temperature. An increase in the feed water temperature corresponds to a relatively higher diffusion rate of water molecules through the membrane, and hence an increased water recovery. Similarly, increased feed water temperature also results in a higher salt diffusion rate through the membrane, and thus higher salt passage and correspondingly lower salt rejection values.

Table 9: Operating Conditions and Effect on RO System Performance

Increase in Condition	Flux Tendency	Rejection Tendency	Reason for Membrane Performance Change
Feed Pressure	↑	↑	Permeate flux is proportional to net driving pressure. Solute permeation rate does not increase with pressure. As a result, flux and salt rejection increase.
Feed Concentration	↓	↓	Net driving pressure decreases by osmotic pressure. At lower salinity (e.g. < 400 mg/l), salt rejection decreases due to the charged effect of RO membrane.
Temperature	↑	↓	Permeate flux increases with temperature (3%/°C) mainly owing to decrease of water viscosity. Solute permeation rate increases with temperature more than permeate flux.
Concentrate Flow Rate	↓	↑	At low flow rate, concentration polarization occurs; the concentration at the membrane surface becomes higher and osmotic pressure increases.

4.2.1.4 pH

The pH tolerance of various SWRO membranes, particularly thin-film membranes, show very stable values of both water recovery and membrane salt rejection, and hence are slightly affected by changes in the system's pH.

Table 10: Feed pH Effect on RO Membrane Rejection

Addition of Chemicals	pH Range (Acidity)	pH Range (Alkalinity)	Reason of Membrane Rejection Change
Acidic Compounds	Low	High	The dissociation of acids at alkaline pH enhances the rejection because of the charge repulsion occurring between compounds and membrane surface.
Basic Compounds	High	Low	The dissociation of alkaline compounds at acidic pH enhances the rejection because of the charge repulsion occurring between compounds and membrane surface.
SiO_2	Low	High	An increase of pH modifies the ionization of silica from silicic acid to silicate, therefore increasing the rejection.
Boron	Low	High	An increase of pH modifies the ionization of boron from boric to borate, therefore increasing the rejection.

4.2.2 Effect of Temperature and Pressure on Salt Rejection

Salt rejection rate is an appropriate measure for the selection of a membrane. While the rejection rate is given for a membrane, it is a function of the operating conditions. Salt rejection increases with reducing temperature, which means that with higher temperatures, much more TDS is in the permeate. This is due to a reduction of solvent viscosity and the pore size effect. Both temperature and pressure regulate the amount of TDS in permeate. In order to produce higher quantities of water with specific quality (i.e. for irrigation applications), particularly with brackish feed water, control of the salt rejection ratio has been analysed. When the salt rejection coefficient increases, less salt concentration appears in permeate and simultaneously higher energy is required. Thus, to mitigate excess salt rejection, the pore size diameter can be increased. While an increase of temperature affected the permeate concentration and flow rate, it proved insufficient to meet the requirements of freshwater production volume. Therefore, physical changes of pore size diameter for membrane are required to tackle the agricultural demand for water.

4.2.3 Effect of Temperature on Osmotic Pressure

Osmotic pressure is the minimum pressure which needs to be overcome by the feed pressure entering the membrane element for water to pass through it, or the minimum pressure which needs to be applied to a solution to prevent the inward flow of water across a semi-permeable membrane. If the temperature increases, the more energy the particles will have and the more collisions that will take place, thus increasing the pressure exerted. The table below shows the result of osmotic pressure at different temperature rates, keeping the concentration of all constituents in the solution constant.

Table 11: Effect of Temperature on Osmotic Pressure

Temp (°C)	Temp (K)	R	Σmi	Posm (kPa)
25	298	8.314	1.1043	2736
25.5	298.5	8.314	1.1043	2740.2
26	299	8.314	1.1043	2745.2
26.5	299.5	8.314	1.1043	2750
27	300	8.314	1.1043	2754.3
27.5	300.5	8.314	1.1043	2759
28	301	8.314	1.1043	2763.5
29	302	8.314	1.1043	2772.7
30	303	8.314	1.1043	2782

4.2.4 Effect of Feed Water Temperature and Recovery on RO Efficiency

Based on the model conditions, as a result of temperature increase mechanisms, water passes more easily through the membrane due to a reduction in the water viscosity. Both the permeate flow rate and concentration increase with temperature; this leads to an increase of recovery and results in an increase in the mechanical power consumption. However, the concentration of TDS in the permeate decreased with the reduction in temperature, leading to a more considerable rejection of TDS. It should be noted that both the water transport and the salt transport increase with increases in temperature. The specific energy increases with reducing temperature because of the corresponding reduction of the solvent transport constant and the reduction of permeate flow rate.

4.2.5 Effect of Feed Spacer on Pressure Drop

The feed spacer is an essential component of spiral wound membrane elements. Feed spacers are manufactured from polymeric materials and optimized to maintain stable performance of membrane elements in a wide range of feed water composition and process parameters. The rate of pressure drop increase mainly depends on quality of the feed water. However, feed spacers of lower initial feed pressure show lower rate of pressure drop increase. Therefore, the use of a smaller feed spacer will develop lower pressure drop and result in smaller power usage of the RO plant over the length of the RO system operation.

4.2.6 Effect of Bio-fouling on RO Membrane

Bio-fouling in RO is a combined result of the following factors:

i. Presence of microorganisms in the feed water.
ii. The RO membrane rejects all microorganisms found in the feed water. As a result, part of the rejected cells remains adhered to the membrane and initiates the process of biofilm formation.
iii. All pretreatment operations prior to the RO module may provide sufficient surface area for microorganisms and bacterial growth. For example, the large surface areas found in media filters, activated carbon beds, or even pipelines connecting various units.

Bio-fouling effects on RO performance are characterised by gradual deterioration in the system performance. This includes a period of rapid decline followed by an asymptotic limit. Performance deterioration includes the following:

i. Decrease in the permeate flux.
ii. Increase in pressure drop.
iii. Decrease in salt rejection.

4.3 Membrane Cleaning

Membrane cleaning is dictated by increase in pressure drop, decrease in permeate recovery, and decrease in salt rejection. It should be stressed that normalised data should be used to correct for temperature effects on system performance. In addition, identification of foulants as well as analysis of feed and outlet water are important factors in determining the proper cleaning solution.

The following is a summary of cleaning methods for various fouling and scaling compounds:

Calcium Carbonate and Metal Oxides Scale:

Clean with low pH water. The water pH is adjusted to 3–4 and sulphuric, hydrochloric, or citric acids are used.

Calcium Sulphate Scale:

Clean with a solution that includes sodium tri-polyphosphate or sodium salt of ethylene di-amine tetra acetic acid.

Silica:

Detergents and hydraulic cleaning.

Organics and Bio-fouling:

Similar solution to calcium sulphate cleaning. In addition, use of detergents and biocides is recommended.

4.4 Energy Recovery

Since energy consumption is the main determinant of final costs of the product, increasing energy efficiency of the plants is of primary concern. The goal of the use of energy recovery is to reduce the Specific Energy Consumption. The pressure exchanger (PX) was used, and the device works on positive displacement and is an isobaric energy recovery device. It contains a ceramic cartridge which is the heart of the device. The cartridge has a feed water end cover, rotor, sleeve and concentrate end cover. The end cover at the concentrate end consists of a High Pressure (HP) Concentrate port for allowing in the HP concentrate and also a low pressure concentrate port for outflowing concentrate (LP OUT). At the feed water end cover side, there are two feed water ports termed LP IN and HP OUT. The high-pressure concentrate is used to direct pressurization of the feed water in the PX device. In order to lubricate the rotor, the flow rate of concentrate is set at somewhat higher flow than the feed water so that a small amount of feed water helps the lubrication of the rotor. The PX device supplies the membranes a portion of feed flow (portion of concentrate) and the high pressure pump supplies the permeate portion of feed water flow. Since some of the feed water is delivered to the membrane through the energy recovery device, the SEC by the system is reduced. For a constant energy recovery of 50 KW, the specific energy consumption and percentage energy recovered for different high pressure pump power is given in the table below.

Table 12: Energy Recovered as High Pressure Pump Power Increases

High Pressure Pump Power (KW)	Specific Energy Consumption Without Energy Recovery (KW/h)	Specific Energy Consumption With Energy Recovery (KW/h)	Energy Recovered (%)
120	69.1	40.5	58.6
125	72	43.2	60
130	74.9	46	61.4
135	77.7	49	63
140	80.6	51.8	64.3
145	83.5	54.7	65.5

V. CONCLUSION AND RECOMMENDATIONS

The importance of water to human existence cannot be overemphasised as it is a basic contributor to life: human, plant and animal. It is a fact that the earth has over 70% of it covered with water, but shockingly less than 4% of it is suited for human consumption. More shocking is the fact that at sea, both crew and passengers find it hard to consume potable water as the water they sail on is salty and has many dissolved particles and as such is not suitable for consumption. The number of persons on a cruise ship makes the fresh water demand very high, making it impossible to depend on water collected from ports; thus desalination is the most viable option.

The region of use is very vital. In this case the West African region is chosen; the capacity of the ship was taken into account in determining the number of persons designed to be on board, and in addition to the consumption rate of the region, the quantity of fresh water to be produced was determined. It is strongly recommended that the reverse osmosis process for desalination be applied to other ship types, as the specific energy consumption rate is low when compared to the thermal process for desalination. The process should also be applied broadly for use on land as it comes in several sizes depending on fresh water production rate and can be applied for use in homes, schools, offices and communities with little or no access to portable water, as it is not restricted to desalinating only sea water but also wastewater, brackish water, etc.

All designs and assumptions were done in accordance with international best practices and with the classification society rules.

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