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Research Article

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Evaluation of the Operational Efficiency and Performance Analysis of a Combined Desalination and salt (NaCl) Production Plant in Indonesia

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ABSTRACT

This case study offers an analysis of the operational efficiency and performance metrics of the Indonesia Desalination and Salt (sodium chloride, NaCl) Production Plant, located in Serang City, Indonesia. The plant stands as a pioneering model in seawater desalination, integrating advanced membrane-based technologies to meet the high demands for desalinated water and food-grade salt production in a region characterized by fluctuating climatic conditions.

The study examines each component of the plant's infrastructure, including the pretreatment system, seawater nanofiltration (SWNF) system, seawater reverse osmosis (SWRO) system, and thermal system. Of particular note is the world's largest commercially available membrane-based food grade brine concentration system, which significantly enhances the plant's overall recovery rate and efficiency. The research delves into the design considerations, process variables, and energy consumption patterns, offering insights from the plant's commissioning phase through its current operations.

The plant's design is tailored to Indonesia's unique geographical and environmental conditions, capable of adapting to the varying characteristics of seawater between monsoon and dry seasons. This adaptability is critical in maintaining consistent production levels while optimizing energy use, with specific power consumption rates monitored and analyzed.

The integration of osmotically assisted reverse osmosis (OARO) systems and advanced brine management technologies further underscores the plant's commitment to innovation and sustainability. These systems not only improve water and salt production efficiencies but also minimize the environmental impact by effectively managing brine discharge.

This case study serves as a vital resource for understanding the complexities and technological advancements in modern desalination and brine concentration systems, offering a blueprint for future projects aiming to balance resource utilization with environmental stewardship.

Keywords: Operational Efficiency, Combined Desalination, Seawater, Production Plant

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Abbreviations:

BL	:	Boundary layer
AL	:	Active layer
SL	:	Support layer
$C_{feed, bulk}$	:	Actual feed solution concentration
$C_{feed, mean}$	:	Feed solution concentration after external concentration polarization occurs
$C_{dilute, bulk}$	:	Actual diluted solution concentration
$C_{dilute, mean}$	:	Diluted solution concentration before internal and external concentration polarization occurs
Jw	:	Water flux
Js	:	Solute flux
ECP	:	external concentration polarization
ICP	:	Internal concentration polarization
Δπ	:	Actual osmotic pressure differences

Introduction

The plant is constructed in the northwest of Java Island, in the Serang City seashore area of the Java Sea. Its membrane-based systems are designed to produce around 21,000 m^3/day desalinated water as permeate, while achieving a total of 202,000 metric ton/year of food grade salt (NaCl) production at 79.5% overall hydraulic plant recovery, with an electrical energy consumption of 9,600 kWh/h in total. Without taking into account the thermal system, the specific energy consumption per produced cubic meter (m^3) of desalinated water was 5.38 kWh/m^3, and the specific energy consumption per produced ton of food grade salt (NaCl) was 376.47 kWh/metric ton-salt. The plant includes a seawater intake system, pretreatment with ultrafiltration (UF) membranes, SWNF membranes, SWRO membranes, Hyrec brine concentration system and a thermal system [1].

Seawater Characteristics

The Java Sea, a shallow body of water with an average depth of 40 meters, lies nestled between the islands of Java, Kalimantan, and Sumatra, with connections to the China Sea to the north, the Flores Sea to the east, and the Indian Ocean to the south.

Table 1: Seawater sample results: Sample 1 (24-July-2023), Sample 2 (21-March-2024)

Test Description	Unit	Sample 1	Sample 2
Physical Tests			
Color (Platinum-Cobalt Scale)	Pt/Co	< 5	< 5
Electrical Conductivity	µS/cm	50,200	45,000
pH	S.U.	8.1	8.2
Temperature	ºC	31.2	30.1
Total Suspended Solids	mg/L	5	8
Total Hardness	mg/L as CaCO3	6,398	5,119
Turbidity	NTU	6.9	7
Cations			
Calcium, Ca^{2+}	mg/L	435	323
Magnesium, Mg^{2+}	mg/L	1,290	1,047
Sodium, Na^{+}	mg/L	10,788	9,645
Potassium, K^{+}	mg/L	382	327
Ammonia, NH^{4+}	mg/L	< 0.01	< 0.01
Barium, Ba^{+}	mg/L	< 0.01	< 0.01
Strontium, Sr^{2+}	mg/L	< 0.01	< 0.01
Iron, Fe^{2+}	mg/L	< 0.01	< 0.01
Manganese, Mn^{2+}	mg/L	< 0.01	< 0.01
Anions			
Sulphate, SO_4^{2-}	mg/L	2,780	2,782
Chloride, Cl^{-}	mg/L	19,360	16,650
Fluoride, F^{-}	mg/L	0.97	1.67
Nitrate, NO_3^{-}	mg/L	0.04	0.01
Bromide, Br^{-}	mg/L	50.2	49.9
Phosphate, PO_4^{3-}	mg/L	< 0.005	< 0.005
Boron, $B3^{-}$	mg/L	2.64	9.1
Silica, SiO_2	mg/L	0.2	0.1
Bicarbonate, $HCO3^{-}$	mg/L	128.5	111.24
Carbonate, CO_3^{2-}	mg/L	0.61	0.56
Carbon Dioxide, CO_2	mg/L	2.99	2.47
Miscellaneous			
Total Coliforms	MPN/100mL	3.7	Not Detected
Biochemical Oxygen Demand, BOD5	mg/L	< 2	< 2
Chemical Oxygen Demand, COD	mg/L	< 2	< 2
Total Dissolved Solids, TDS	mg/L	35,220	30,950

Process Description

Raw seawater is routed by gravity to the underground seawater intake basin with an automatic travel band screen from the intake head structure in the seabed. After injecting sodium hypochlorite (NaOCl) for disinfection in this basin, seawater is introduced to the UF units to eliminate colloidal particles and microorganisms. Ultrafiltered water passes through a two-stage SWNF system and then to a two-stage SWRO system. While desalinated water is produced on the SWRO permeate, the SWRO concentrated brine stream is processed to the Hyrec brine concentration systems with OARO technology to further concentrate up to 16,4% as sodium chloride (NaCl) brine before being fed to the thermal system. The diluted stream on Hyrec's brine concentration system is fed back into the nanofiltration (NF) permeate tank and mixes with the SWNF permeate before being fed to the SWRO system. The thermal system includes falling film evaporator (FFE) to increase the brine concentration which is produced from Hyrec's brine concentration systems up to saturation limits of 26% NaCl brine solution, and forced circulation to the crystallizer system to produce ≥ 99.5% purity food grade salt (NaCl). Figure 1 illustrates the system's mass balance diagram.

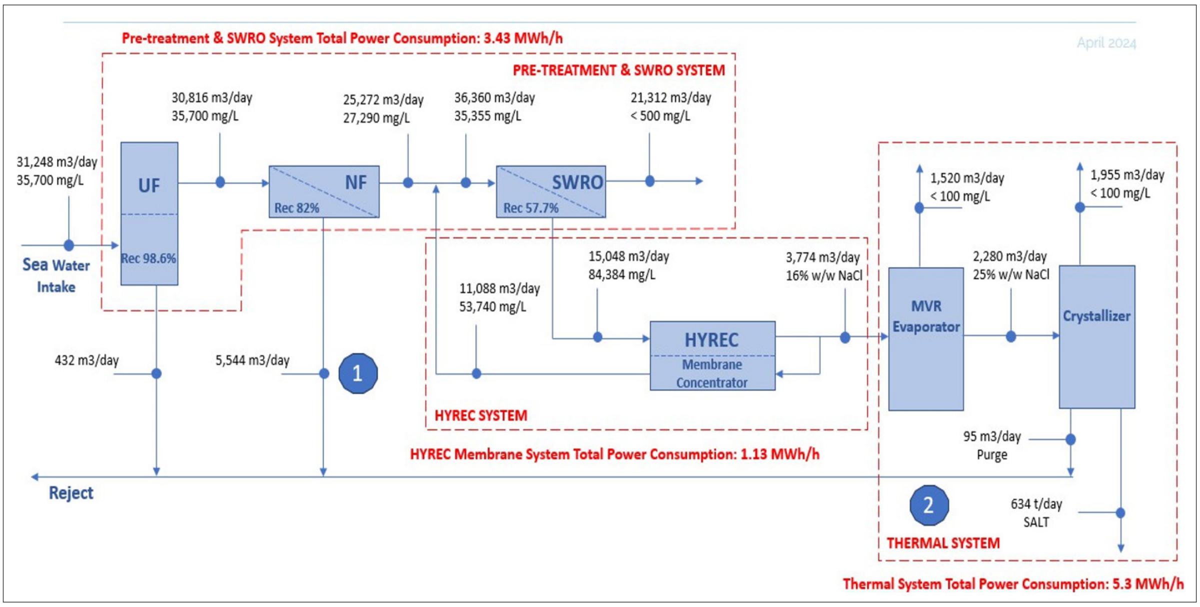

Figure 1: System mass balance

Seawater Intake System

Seawater intake design and construction is a vital part of downstream pretreatment systems to supply a consistent quantity and quality of seawater. While designing the intake system to be installed, locations must be evaluated within physical, chemical, and biological variations of seawater characteristics, tidal flows, wave currents, etc. The environmental effects must be considered as well.

Photo 1: Seawater intake head structure

The intake pipe is connected to a structure skid by a flange, and a cathodic protection is applied to prevent corrosion. To avoid fish and jellyfish getting sucked in through the intake pipeline, 0.45 m/s and 0.75 m/s velocities are considered for sizing the pipe as nominal and design flows respectively. Based on these considerations and calculations, the pipe size selected is DN1200, made of HDPE (PE100-SDR21) pipe material which is considered for its flexibility, free maintenance, and ease of installation. The pipeline is buried on the seabed with concrete collars installed every 3 meters along the pipeline route to provide a stable structure in case of strong wave activity. To control microbiological growth, which can decrease the cross-section area on the pipeline and can increase pressure drop, a chlorine pipeline is allocated to perform intermittent shock chlorination. Shock chlorination is performed once a week for 1 hour long by dosing 8.0 – 9.0 mg/L sodium hypochlorite (NaOCl).

Seawater Intake Basin

The seawater intake basin is an underground concrete reservoir comprising of four distinct chambers, which can be individually isolated using stoplogs to facilitate maintenance. The intake pipe connects to the first chamber, where a disinfection chemical, sodium hypochlorite (NaOCl), is injected. Continuous dosing of NaOCl into this chamber is manually controlled to maintain a free residual chlorine concentration of 0.2 to 0.3 mg/L, as monitored by a free chlorine analyzer located at the basin outlet. The disinfection chemical used is a 12% w/w concentration of NaOCl, with typical dosing concentrations ranging from 0.8 to 1.0 mg/L.

Following the introduction of NaOCl, the raw seawater is directed into two identical, separate channels equipped with automatic traveling band screens of 6 mm mesh to prevent marine organisms and foreign materials from proceeding further. The cleaning of the screens is accomplished by well pumps installed downstream, which feed water to spray nozzles. The removed debris is collected in a perforated trash basket, where water is drained through a trench, and the particles are manually disposed. Wetted parts of the traveling band screens and stop logs, including the frames, are fabricated from duplex material, and are further protected from corrosion by additional cathodic protection.

The filtered raw seawater is collected in a common chamber before being routed to a final chamber, where the suction nozzles for the ultrafiltration system feed pumps are situated. Turbidity, total organic carbon, and pH levels are monitored by a circulation pump that delivers water to these measuring stations.

Ultrafiltration System

Disinfected and roughly filtered water in the intake basin is fed into a three-train UF unit by variable-frequency drive (VFD) feed pumps to vary flux throughout the filtration step, and discharge lines of the pumps are interconnected to allow cross operation. Suction heads of feed pumps have 5 mm perforated high density polyethylene (HDPE) basket filters to protect the pumps from large foreign particles. Cleaning of the basket filters is done manually, and differential pressure is continuously monitoring between inlet and outlet streams. Also, before entering the pressure driven UF unit, the raw seawater is met with a 200 µm mesh sized automatic self-cleaning mechanical filter manufactured with a fiberglass reinforced plastic (FRP) body and duplex strainer to increase the efficiency of the UF units. Cleaning of this filter is based on Bernoulli's principle.

The UF system is designed to maintain the necessary flow to produce a constant amount of salt in advanced processes while keeping the SDI15 below 2.5 to protect the downstream membranes and considering peaks of feed seawater turbidity levels during filtration. Each UF train has an average filtering capacity between 390 m^3/hour and 438 m^3/hour, depending on the seawater's salinity. Additionally, when the turbidity level is high in the feed seawater stream, the filtration time for recovering flux, transmembrane pressure (TMP), and permeability after backwashing is expected to be between 40 to 60 minutes.

The typical flux for seawater ultrafiltration systems generally ranges from 50 to 80 liters per square meter per hour (LMH). This range can vary depending on specific operational conditions, water quality, and the design of the UF system. Overall, the typical flux for seawater ultrafiltration systems is carefully chosen to balance efficiency, membrane longevity, operational costs, and the quality of the treated water.

In designing ultrafiltration units, an average of 65 LMH permeate flux is considered, and the outside-in filtration direction is preferred for its ease of cleaning, better solids handling, improved fouling control, and lower power consumption due to low TMP is expected.

Ultrafiltration modules type PVDF, nominal pore size 0.04 µm are selected to meet the above-mentioned requirements, and more than 98% hydraulic recovery is achieved.

Based on the above-mentioned working conditions, Case-1 represents the worst-case scenario for membrane fouling. Therefore, it is crucial to monitor TMP to ensure recovery after air scouring and daily alkali maintenance cleaning (MC). Below Photo 2 is a trend that shows TMP changes between air scourings and after alkali MC. Even with the peak turbidity level, air scouring can keep the TMP below 0.65 bar and chemical cleaning also recovers the TMP completely.

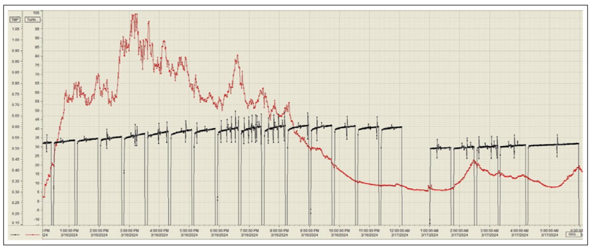

Photo 2: UF transmembrane pressure (TMP)/turbidity trend

Seawater Nanofiltration System

The SWNF system represents an advanced technological approach to effectively separate divalent and larger monovalent ions, organic molecules, and other contaminants from water, while permitting the passage of smaller monovalent ions and water molecules. NF membranes are composed of thin, polymeric films engineered to achieve high selectivity and flux. These membranes are typically fabricated through interfacial polymerization, resulting in a highly cross-linked polyamide layer that serves as the selective barrier. The structure of the membrane is designed to withstand the high pressures required for seawater filtration, up to and exceeding 30 bar, and to resist fouling and chemical degradation over prolonged operational periods. The filtration process in NF systems is driven by a pressure gradient, where seawater is forced through the NF membrane. The mechanism combines size exclusion and charge effects to achieve separation. Size exclusion relies on the physical sieving of particles larger than the membrane pores, while charge effects exploit the electrostatic interactions between the charged membrane surface and ionic species in the water. This dual mechanism enables the efficient rejection of multivalent ions (e.g., Mg^{2+}, Ca^{2+}, SO_4^{2-}) and organic compounds, while allowing most monovalent ions (e.g., Na^+, K+, Cl^-) and water to pass through. NF membranes do not tolerate free chlorine; therefore, sodium bisulfite is used upstream the NF to remove it.

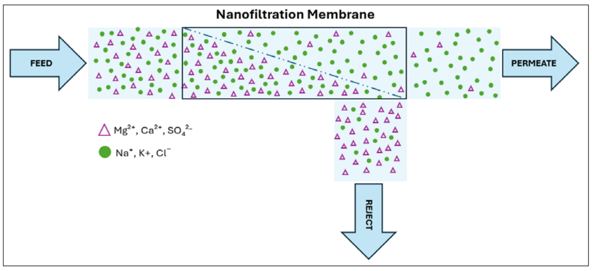

Figure 2: Typical ionic rejection of NF membranes

The primary objective of the plant is to consistently produce food-grade salt (NaCl). Therefore, it is essential to choose nanofiltration membranes that can effectively remove impurities like Mg^{2+}, Ca^{2+}, and SO_4^{2-} with a high rejection rate while keeping salt (NaCl) rejection to a minimum. The presence of these impurities increases the purge volume in the thermal system, leading to salt loss and lowers the plant's recovery rate. Additionally, minimizing salt rejection helps to reduce the number of membranes needed and decreases specific energy consumption.

Veolia's DK-440 nanofiltration spiral wound membranes were tested on a pilot basis during 1 year and compared with other membrane brands. The DK-440 membrane results were the most satisfactory with projections matching the actual outputs and the DK-440 membrane had an optimal fractionation ratio of divalent/monovalent ions. This provided a solid foundation for designing the further brine concentration process. The calculated salt loss in the permeate stream of each SWRO system is 0.18 metric ton/h, and the total purge in the thermal system is 1.2 metric ton/h. To achieve a net salt production of 25.5 metric ton/h, each NF system needs to produce 9.08 metric ton/h of salt from the permeate stream, while adapting to varying salinity levels of the feed stream.

Nanofiltration systems are designed to recover as much salt as possible from the feed stream while ensuring a high recovery rate. This is accomplished using a two-stage design. In this setup, the rejected stream from the first stage is fed into the second stage, thereby enhancing both the recovery rate and the salt concentration in the final permeate stream. Additionally, to optimize the distribution of flux and mitigate the excess recommended membrane recovery rate, an interstage booster pump is incorporated into between stages. This ensures a more efficient and balanced operation throughout the filtration process. Below, Table 2 is the membrane projection data from Veolia's Winflows Design Simulator based on worst case scenario which is low salinity inlet feed stream.

Table 2: Winflows Design Simulator projection data for seawater NF system

Veolia Water Technologies & Solutions

Results Summary

Flow Data	m3/hr	Analytical Data	mg/L
Raw Feed:	438.00	Raw Feed TDS	30947.61
Product:	359.10	Product TDS	25237.43
Concentrate:	78.92	Concentrate TDS	56924.82

System Data — Single Pass Design

Temperature: 30 °C

System Recovery: 82.00%

Average Flux (lmh), Pass and Stage

Pass	Average	Stage 1	Stage 2
Pass 1	20.34	20.93	18.79

Array Data

Recovery %: 82.00 Conc. TDS(mg/l): 56924.82 Conc. Flow: 78.92 m3/h

Stage	Total		Element Type	Flow, m3/hr		Pressure, bar		Perm TDS
	Housing	Element		Feed	Perm	Feed	DP	mg/l
1	39	312	DK-440	438.00	266.95	9.05	1.12	24793.28
2	15	120	DK-440	171.06	92.15	14.93	1.19	26524.08
Total	54	432						

Analytical data

Cation	Product (mg/l)	Feed (mg/l)	Conc (mg/l)	Anion	Product (mg/l)	Feed (mg/l)	Conc (mg/l)
Ca	89.47	323.36	1387.43	SO4	11.09	2781.91	15388.21
Mg	52.24	1047.07	5573.17	Cl	15133.55	16657.53	23585.80
Na	9483.42	9645.33	10378.62	F	1.65	1.67	1.80
K	315.04	327.46	383.86	NO3	0.01	0.01	0.01
NH4	0.00	0.00	0.00	Br	49.04	49.89	53.72
Ba	0.00	0.00	0.00	PO4	0.00	0.00	0.00
Sr	0.00	0.00	0.00	B	9.16	9.15	9.07
Fe	0.00	0.00	0.00	SiO2	0.10	0.10	0.10
Mn	0.00	0.00	0.00	H2S	0.00	0.00	0.00
TDS mg/l	25237.43	30948.82	56924.82	HCO3	92.50	105.14	162.61
pH	7.00	7.00	7.00	CO2	6.72	6.66	6.37
				CO3	0.15	0.19	0.40
Saturation Data							
BaSO4 %	0.00	0.00	0.00	CaF2 %	7.22	23.44	82.16
CaSO4 %	0.03	19.79	**246.46**	SiO2 %	0.08	0.08	0.08
SrSO4 %	0.00	0.00	0.00	LSI	-1.05	-0.50	0.16
Struvite %	0.00	0.00	0.00	Pi bar	20.05	22.53	34.48

The nanofiltration system produces high quality permeate, formed mainly by sodium chloride (NaCl), with the concentration of the monovalent ions over 150 times the concentration of divalent ions. To ensure the system maintains consistent salt production, the permeate lines electrical conductivity is continuously monitored using an online electrical conductivity sensor.

One of the major challenges in NF systems is the scaling or fouling of the membrane, which can significantly reduce the efficiency and lifespan of the system. Scaling occurs when dissolved salts exceed their solubility limits and precipitate onto the membrane surface. Common scalants include calcium carbonate ($CaCO_3$), calcium sulfate ($CaSO_4$), calcium fluoride (CaF2), barium sulfate ($BaSO_4$), and silica (SiO_2). The selection and dosage of antiscalants depend on several factors including the water chemistry, type of membrane, and system design. The dosage is determined based on the scaling potential of the feedwater which can be calculated from the hydraulic recovery target of the membrane system and assessed using various indices like the Langelier Saturation Index (LSI) or the Stiff and Davis Stability Index (S&DSI) for calcium carbonate, combined with the study of the solubility saturation limit for calcium sulphate.

Carbonate scaling can be significantly reduced by precisely adjusting the pH levels of the feed water before introduction to the nanofiltration system, specifically by dosing acid to maintain a pH range of approximately 6.8 to 7. On the other hand, to prevent the formation of calcium sulfate ($CaSO_4$) and calcium fluoride (CaF_2) precipitates, Veolia's Hypersperse MDC706 antiscalant is continuously dosed before the nanofiltration process. Figure 3 and Figure 4 below illustrate the saturation indices before and after pH adjustment and antiscalant dosage, respectively, calculated by Veolia's Argo analyzer software.

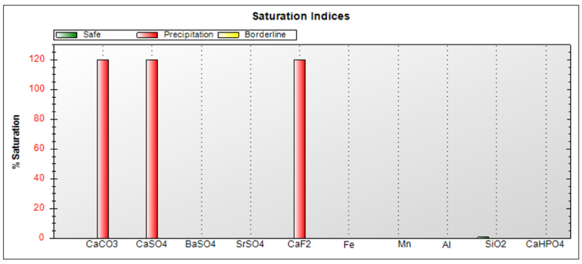

Figure 3: Before pH adjustment and antiscalant dosing in NF system

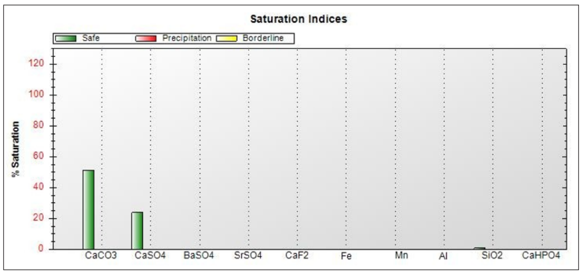

Figure 4: After pH adjustment and antiscalant dosing in NF system

The graphs in the following section show the operational results in filtration mode of the NF during the initial 1,500 hours. Throughout this period, we kept a close eye on rejection rates and selectivity factor to assess how well the membranes were performing. Additionally, we also paid attention to power consumption, as it can indicate the efficiency of the system. By continuously monitoring these factors, we could evaluate the overall performance of the nanofiltration system over time.

Nanofiltration Membrane Performance Analysis

Rejection Rate

To calculate the rejection rates of magnesium, calcium, and sulfate from a nanofiltration system, we need to know the concentrations of these ions in both the feed (influent) and the permeate (effluent) streams. The rejection rate is a measure of how effectively the membrane removes these ions from the feed stream.

$$R = \frac{(C - C')}{C} \times 100$$

were,

R: The rejection rate [%]

C: The initial concentration of the ion in the feed solution [mg/L]

C': The concentration of the ion in the permeate solution after passing through the membrane [mg/L]

Selectivity Factor

The selectivity factor for nanofiltration membranes quantifies the membrane's ability to preferentially allow certain solutes to pass through while retaining others. It is typically defined as the ratio of the rejection rates of monovalent and multivalent ions.

$$SF = \frac{100 - R_{mon}}{100 - R_{multi}}$$

were,

SF : The average selectivity factor [-]

R_{mon} : The rejection percentage of monovalent ions [%]

R_{multi} : The rejection percentage of multivalent ions [%]

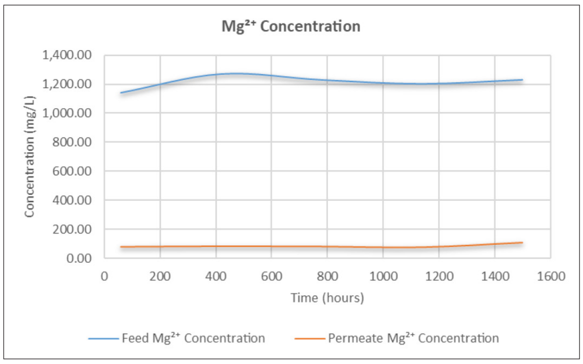

Figure 5: Mg^{2+} concentration at NF inlet and NF permeate streams

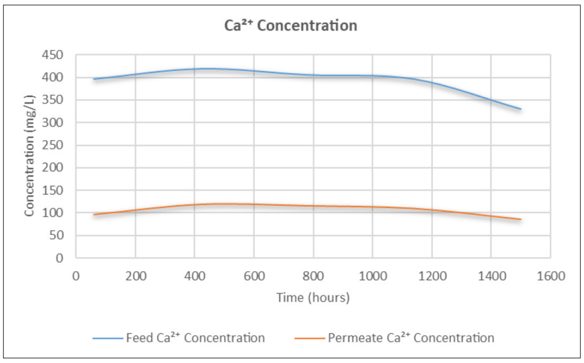

Figure 6: Ca^{2+} concentration at NF inlet and NF permeate streams

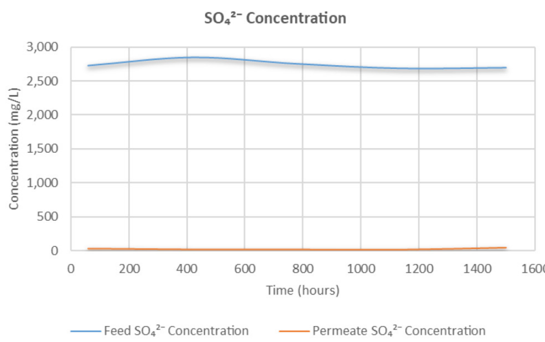

Figure 7: SO_4^{2-} concentration at NF inlet and NF permeate streams

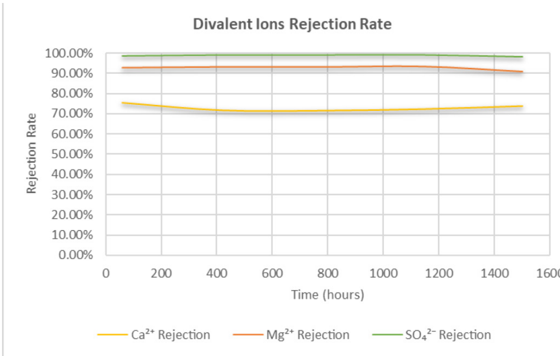

Figure 8: Mg^{2+}, Ca^{2+}, SO_4^{2-} NF rejection rates

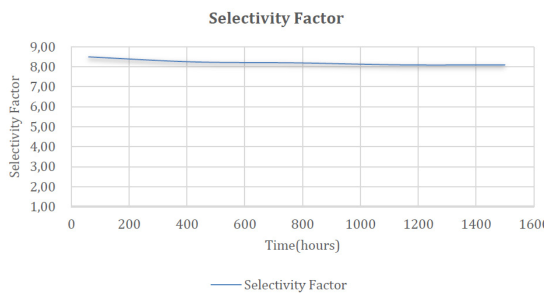

Figure 9: Nanofiltration average selectivity factor (passage of monovalent ions vs passage of multivalent ions)

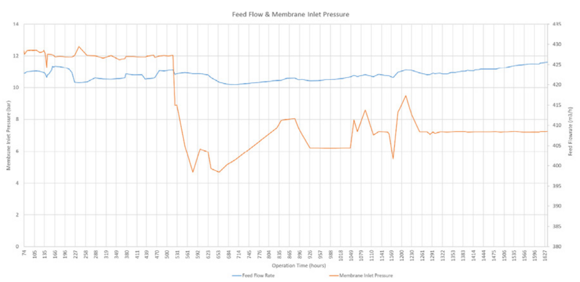

Figure 10: Nanofiltration feed flow & membrane inlet pressure

In summary, a higher rejection rate of Mg^{2+}, Ca^{2+}, SO_4^{2-} ions and higher selectivity factor indicates a greater ability of the membrane performance. The results show that, neglecting small measurement errors for ion composition, multivalent ion separation performances and selectivity factors are still almost constant after 1,500 hours of operating time and within the projected values by Veolia's Winflows Design Simulator, indicating the criticality of robust pretreatment in nanofiltration applications. Additionally, conceptually by removing divalent ions and reducing the scaling potential, a nanofiltration system helps to maintain a higher flux through the seawater reverse osmosis membranes and reduces the need for chemical scale inhibitors and enhance the recovery and reduce fouling potential of seawater reverse osmosis systems.

Seawater Reverse Osmosis System

SWRO is a highly effective and widely adopted method for desalinating seawater to produce fresh water. This technology has become crucial in regions with limited freshwater resources, providing a sustainable solution to water scarcity. Beyond producing fresh water, SWRO also generates a concentrated saline solution known as brine, which is the main consideration in the plant. SWRO is a sophisticated filtration process in which seawater is forced through a semi-permeable membrane under high pressure. This specialized membrane permits water molecules to pass while effectively retaining dissolved salts and other minerals, thereby producing fresh water. The SWRO process is notably energy-intensive, largely due to the substantial pressures required, which can reach up to 80 bar. The efficiency and effectiveness of the SWRO process are directly influenced by the osmotic pressure, as higher salinity levels require greater pressure to achieve the desired performance.

To minimize membrane degradation and maintain system sustainability, the operating pressure was carefully considered not to exceed 75 bar. Additionally, maximizing the concentration of salt in the concentrated stream was another critical design parameter. Consequently, the SWRO system was configured in two stages, utilizing different membrane models at each stage. The first stage employs Veolia's AC-440 spiral wound membranes, while the second stage uses Veolia's AE-440 spiral wound membranes. This configuration was chosen because AC Series membranes have a tighter structure compared to AE Series membranes, allowing the first stage to concentrate the inlet stream with a higher rejection rate under the applied pressure. The second stage then enhances system recovery, achieving a concentration of around 8.0% w/w TDS on the system outlet brine stream with a total of between 58% to 60.6% recovery which also varies with the feed concentration and flow rate to maintain constant salt concentration in the filtration process. Below Table 3 is the membrane projection from Veolia's Winflows Design Simulator based on the worst case scenario low salinity inlet).

Based on the saturation data, CaF2 precipitation is expected because the saturation limits will be exceeded. However, when considering the antiscalant dosing, it's important to remember that the antiscalant will accumulate in the concentrate stream. This stream will be processed by the OARO system to further concentrate it. The OARO system also produces a diluted stream that feeds back to the SWRO inlet. Therefore, the antiscalant dosing for the SWRO inlet stream must be calculated iteratively to ensure efficient dosing. Figure 11 below shows the antiscalant dosing concentrations based on the needs of the OARO system. As a result, the antiscalant dosage concentration has been set at 1.5 mg/L for the SWRO system to meet the requirements of the SWRO & OARO systems.

Table 3: Winflows Design Simulator projection data for seawater reverse osmosis system

Veolia Water Technologies & Solutions

VEOLIA

Results Summary

Flow Data	m3/hr	Analytical Data	mg/L
Raw Feed:	512.00	Raw Feed TDS	33419.99
Product:	310.40	Product TDS	287.60
Concentrate:	201.98	Concentrate TDS	84330.45

System Data | **Single Pass Design**

Temperature: 30°C

System Recovery: 60.63%

Average Flux (lmh), Pass and Stage

Pass	Average	Stage 1	Stage 2
Pass 1	17.50	24.36	6.63

Array Data

Recovery %: 60.60 Conc. TDS(mg/l): 84330.45 Conc. Flow: 201.98 m3/h

Stage	Total		Element Type	Flow, m3/hr		Pressure, bar		Perm TDS
	Housing	Element		Feed	Perm	Feed	DP	mg/l
1	38	266	AC-440	512.00	264.85	74.95	1.10	113.24
2	24	168	AE-440	247.42	45.55	73.60	1.08	1302.13
Total	62	434						

Analytical data

Cation	mg/l Product	mg/l Feed	mg/l Conc	Anion	mg/l Product	mg/l Feed	mg/l Conc
Ca	0.22	124.68	310.27	SO4	0.02	15.57	38.77
Mg	0.13	73.18	182.12	Cl	169.26	20403.32	50575.84
Na	107.16	12776.31	31668.22	F	0.04	2.22	5.48
K	5.18	424.86	1050.65	NO3	0.00	0.01	0.03
NH4	0.00	0.00	0.00	Br	0.77	66.06	163.43
Ba	0.00	0.00	0.00	PO4	0.00	0.00	0.00
Sr	0.00	0.00	0.00	B	2.85	12.28	26.33
Fe	0.00	0.00	0.00	SiO2	0.00	0.13	0.33
Mn	0.00	0.00	0.00	H2S	0.00	0.00	0.00
TDS mg/l	287.60	34024.09	84330.45	HCO3	1.98	125.24	307.86
pH	5.53	7.00	7.14	CO2	8.13	8.00	8.22
				CO3	0.00	0.22	1.11
Saturation Data							
BaSO4 %	0.00	0.00	0.00	CaF2 %	0.00	16.19	**167.46**
CaSO4 %	0.00	0.04	0.14	SiO2 %	0.00	0.11	0.27
SrSO4 %	0.00	0.00	0.00	LSI	-6.15	-0.83	-0.05
Struvite %	0.00	0.00	0.00	Pi bar	0.25	27.20	70.98

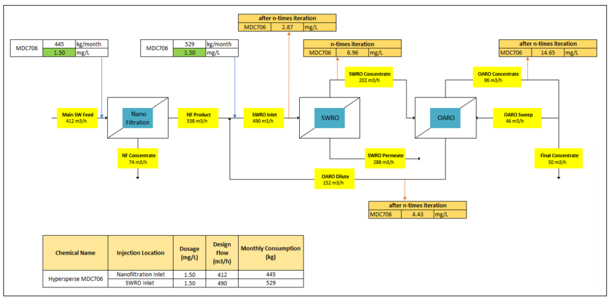

Figure 11: Overall plant antiscalant dosing calculation

The design of the SWRO system considers the total power consumption as one of the main critical factors of this technology. The efficiency and effectiveness of SWRO systems largely depend on the performance of high-pressure pumps and energy recovery devices, making these devices essential components to ensure efficient, reliable, and cost-effective salt separation. Typically, high-pressure pumps provide the necessary pressure to drive the separation process, while energy recovery devices capture and reuse energy from the brine stream, significantly reducing overall energy consumption and operational costs.

The seawater reverse osmosis racks are integrated with high pressure pumps and energy recovery devices. By combining this equipment, lower energy consumption is achieved with the variation of feed water salinity. During 1,500 hours of operation, pump efficiencies were monitored as 90% for the high-pressure pumps, and 92% efficiency for the energy recovery device. Average specific power consumption was observed for seawater reverse osmosis systems average 3.53 kWh/m3-desalinated water.

Power Consumption Calculations

Power consumption for pumps,

$$W = \frac{Q_f \times (P_i = P_o)}{600 \times \eta_p \times \eta_m \times \eta_{VFD}}$$

where,
W : The consumed power [kWh/h]
Q_f : The flowrate of pump [L/min]
P_i : The inlet pressure of pump [bar]
P_o : The outlet pressure of pump [bar]
η_p : The pump efficiency [%]
η_m : The motor efficiency [%]
η_{VFD}: The frequency driver efficiency [%]

Specific Energy Consumption,

$$SEC = \frac{E}{Q_p}$$

where,
SEC : The specific energy consumption [kWh/m^3]
E : The total power consumption for system [kWh/h]
Q_p : The desalinated water (permeate) flow rate [m^3/h]

Evaluating the performance of seawater reverse osmosis membranes involves various parameters and calculations. The information below provides a detailed overview of this evaluation criteria and the associated equations.

Seawater Reverse Osmosis Membrane Performance Analysis
Salt rejection,

$$R = \left(1 - \frac{C_p}{C_f}\right) \times 100$$

where,
R : The salt rejection [%]
C_p : The salt concentration in the permeate stream [mg/L]
C_f : The salt concentration in the feed water stream [mg/L]

Permeate flux,

$$J_w = \frac{Q_p}{A}$$

where,
J_w : The permeate flux [L/m^2.h or LMH]
Q_p : The desalinated water (permeate) flow rate [L/h]
A : The membrane area [m^2]

Osmotic pressure,

$$\pi = R \times (T + 2733) \times \sum M_i$$

where,
π : The osmotic pressure [bar]
R : The universal gas constant [0.0809 L·bar/mol·K]
T : The temperature of solute [ºC]
ΣM_i: The sum of the molar concentration of all constituents of solute [mol/L]

Water permeability coefficient,

$$A = \frac{J_w}{NDP}$$

where,
A : The water permeability coefficient [L/m²·h·bar]
J_w : The permeate flux [L/m^2.h or LMH]
NDP : The net driving pressure ($\Delta P - \Delta\pi$) [bar]
ΔP : The applied pressure [bar]
$\Delta\pi$: The osmotic pressure difference [bar]

Salt permeability coefficient,

$$B = J_w\left(\frac{1}{R} - 1\right)$$

where,
B : The salt permeability coefficient [L/m²·h]
J_w : The permeate flux [L/m^2.h or LMH]
R : The salt rejection [-]

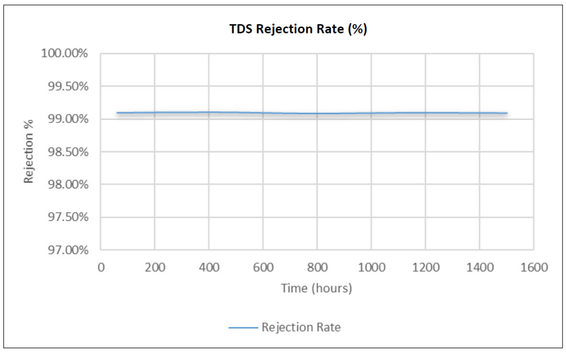

Figure 12: Total dissolved solids (TDS) rejection in SWRO

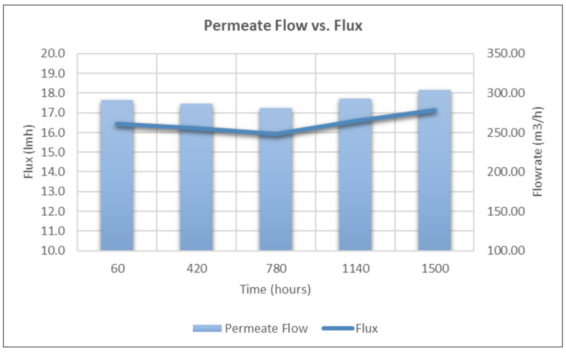

Figure 13: SWRO permeate flow (m^3/h) vs permeate flux (lmh)

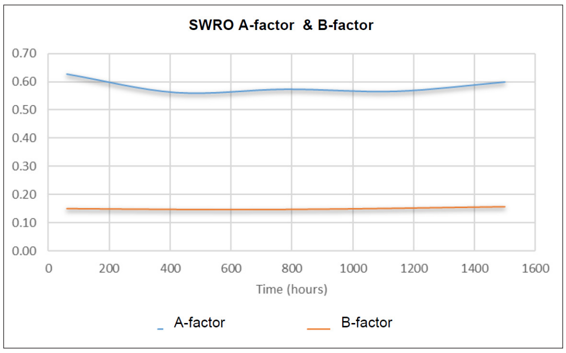

Figure 14: SWRO membrane A-factor & B-factor

Thanks to the NF pretreatment, the majority of the salts going into the SWRO feed is mainly NaCl. To simplify the operation and monitoring of the SWRO system we use the total dissolved solids (TDS) to evaluate the SWRO performance on a regular basis, whereas the actual NaCl rejection is observed only sporadically.

The A & B – factors are dimensionless coefficients applied to the actual A & B coefficients to correct the water permeability and salt permeability respectively to align the actual figures observed onsite versus the calculated figures by Veolia's Winflows Design Simulator. For example, an A-factor = 1 means that the water permeability onsite matches exactly the nominal characteristics of the membrane, while an A-factor < 1 indicates a lower permeability than nominal. The same reasoning applies to the B-factor (salt permeability). The Figure 14 above shows clearly that the SWRO membranes suffered compaction due to the high pressures (75 bar) and high temperatures (approximately 30°C or slightly above) resulting in higher SWRO membrane feed pressure than expected, as well as higher TDS rejection rates.

The evaluation of the SWRO membrane showed excellent operational efficiency, especially in managing the concentrate stream. The system consistently produced a concentrate stream with about 8% salinity, indicating precise control over concentration polarization. This concentration level not only demonstrates effective salt rejection, but also proves that no scaling or fouling of the membranes is observed. Additionally, the almost steady concentrate flow rate demonstrates the membrane's ability to handle high salinity without reducing throughput. The stable composition of the concentrate stream highlighted the flexibility of the membrane and the efficiency of the system to maintain high performance under changing conditions. These factors collectively demonstrated the good condition of the SWRO membrane and ensured sustainable and efficient desalination with minimal maintenance requirements.

Osmotically Assisted Reverse Osmosis System

Osmotically assisted reverse osmosis (OARO) is an advanced method for treating brine produced by conventional SWRO systems. This hybrid membrane technology combines the principles of forward osmosis (FO) and reverse osmosis (RO). In osmotically assisted reverse osmosis (OARO), a draw solution creates an osmotic pressure gradient, which helps to overcome some limitations of traditional SWRO such as burst pressure limits of membranes. Specifically, a draw solution with high osmotic pressure is used on one side of a semipermeable membrane, while the feed water, a concentrated seawater stream, is on the other side. This osmotic pressure gradient facilitates the movement of water through the membrane and allows continual concentration of ultra-saline brine, assisting the reverse osmosis process and reducing the need for high hydraulic pressure. Consequently, energy consumption is lower. The concentrated brine produced from an OARO system can be two to three times more concentrated than that concentrated stream from traditional RO systems. This highly concentrated brine is useful for industries such as mineral extraction and chemical production. Additionally, the reduced volume of brine decreases capital expenditures (CAPEX) and operating expenses (OPEX) for further evaporation processes, making it a cost-effective and efficient solution. Below Figure 15 illustrates the osmotically assisted reverse osmosis membrane module.

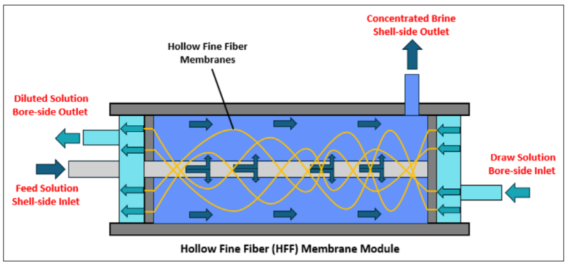

Figure 15: Osmotically assisted reverse osmosis membrane module

Hyrec's patented OARO system is a crossflow type configuration. In crossflow OARO, the concentration of brine in the feed solution remains relatively uniform along the membrane surface due to the perpendicular flow of the draw solution. This configuration promotes turbulent flow and reduces concentration polarization, resulting in a more even distribution of brine concentration.

Concentration polarization refers to the accumulation of solutes near the membrane surface during the filtration process, which creates a concentration gradient. This phenomenon has significant effects on the performance of OARO systems, particularly in high salinity applications such as salt production.

Formation of a Concentration Gradient

Process Overview: In OARO, a high-concentration feed solution (e.g., seawater or brine) is subjected to pressure, forcing water through a semi-permeable membrane while retaining most of the solutes (salts).

Solute Accumulation: As water permeates through the membrane, solutes are rejected and accumulate in the boundary layer adjacent to the membrane surface.

Diffusion and Permeation

Water Transport: Water molecules move from the feed side (high concentration) to the permeate side (low concentration) driven by the applied pressure and osmotic pressure difference.

Boundary Layer Formation: Near the membrane surface, solutes build up, forming a concentrated boundary layer. This layer is more concentrated than the bulk feed solution due to the rejected solutes.

Reduced Water Flux

Decreased Driving Force: The increased concentration of solutes in the boundary layer reduces the effective osmotic pressure difference across the membrane. This reduction lowers the driving force for water transport.

Water Flux Impact: As a result, the water flux (rate of water permeation) through the membrane decreases because the osmotic pressure difference is a key driver for water movement in OARO.

Increased Salt Concentration

Localized Concentration: The solute concentration near the membrane surface can become significantly higher than in the bulk feed solution.

Membrane Fouling: High local concentrations can lead to scaling (precipitation of salts) or fouling (accumulation of organic or biological materials) on the membrane surface, which further diminishes membrane performance and lifespan.

To mitigate concentration polarization and maintain optimal performance in osmotically assisted reverse osmosis systems, several strategies can be employed:

Crossflow Filtration
Mechanism: The feed solution flows tangentially across the membrane surface, which helps to sweep away accumulated solutes and minimize the thickness of the boundary layer.

Benefit: Reduces the concentration of solutes near the membrane, maintaining a higher osmotic pressure difference and enhancing water flux.

Membrane Surface Modifications
Coatings and Treatments: Applying hydrophilic or anti-fouling coatings to the membrane surface can reduce solute adsorption and enhance solute rejection.

Enhanced Properties: Modifications can improve the membrane's resistance to fouling and scaling, maintaining higher performance over time.

Operating Conditions Optimization
Flow Rate: Adjusting the feed flow rate can control the shear forces at the membrane surface, which helps to reduce the concentration boundary layer.

Pressure and Temperature: Optimizing operating pressure and temperature can enhance the permeate flux and reduce the impact of concentration polarization.

Concentration polarization is a critical factor in the performance of OARO membranes used for higher concentration brine production. It leads to reduced water flux and increased risk of membrane fouling. By employing above mentioned strategies, the negative impacts of concentration polarization can be mitigated, ensuring more efficient and sustainable operation of OARO systems. Below Figure 16 illustrates the concentration polarization phenomena.

The Hyrec OARO system is specifically designed by using hollow fiber membranes to concentrate brine in a four- stage configuration, increasing the NaCl concentration from 8% w/w to 16% w/w, with corresponding flow rates of 202 m³/h and 50 m³/h, respectively. This process utilizes 360 pieces of membranes per train, operating at a pressure below 65 bar.

Hyrec Osmotically Assisted Reverse Osmosis Membrane Performance Analysis
Flux,

$$J_w = \frac{\frac{(\Delta Q_c + \Delta Qd)}{2}}{A}$$

where,
J_w : The permeate flux [L/m².h or LMH]
ΔQ_c : The stage based flowrate differences on concentrate stream [L/h]
ΔQd : The stage based flowrate differences on dilute stream [L/h]
A : The membrane area [m2]

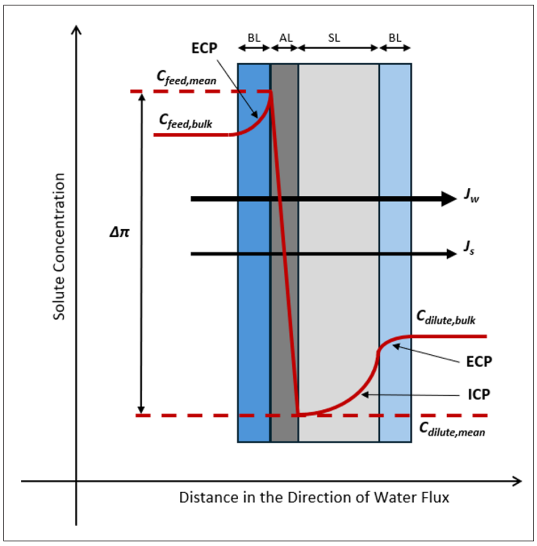

Figure 16: Illustration of internal and external concentration polarization

Water permeability coefficient [A-value],

$$A - value = \frac{J_w}{[(P_c - P_d) - (\pi_c - \pi_d)]}$$

where,
A : The water permeability coefficient [L/m²·h·bar]
J_w : The permeate flux [L/m2.h or LMH]
P_c : The concentrated stream pressure [bar]
P_d : The diluted stream pressure [bar]
π_c: The concentrated stream osmotic pressure [bar]
π_d: The diluted stream osmotic pressure [bar]

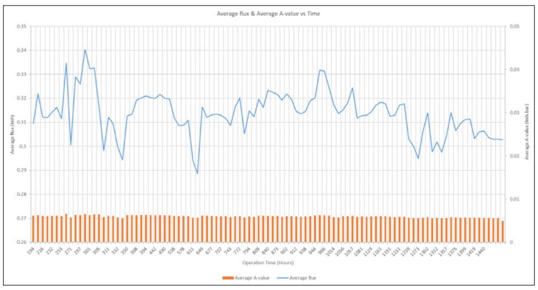

Figure 17: Hyrec OARO average flux & average A-value in operation

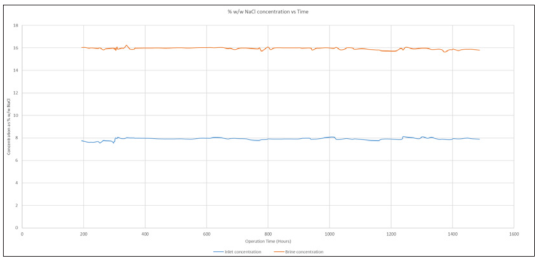

Figure 18: Hyrec OARO inlet and brine concentration in operation

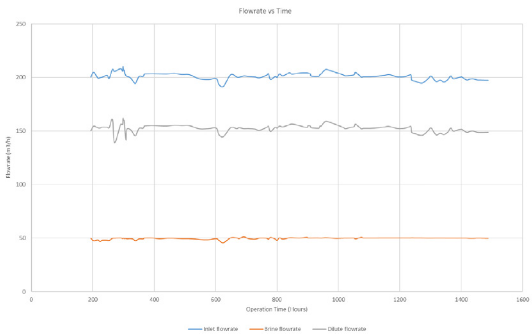

Figure 19: Hyrec OARO flowrates on each stream on operation

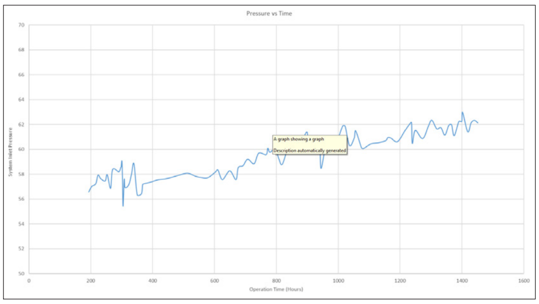

Figure 20: Hyrec OARO membrane inlet pressure on operation

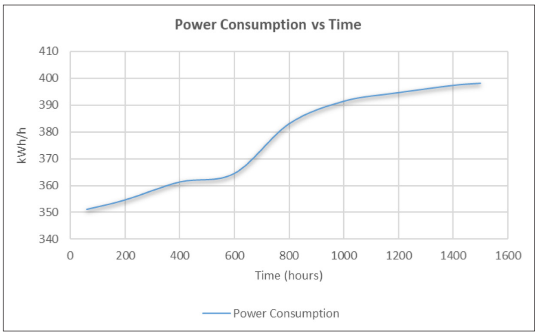

Figure 21: Hyrec OARO power consumption in operation

Hyrec OARO systems are well-established and have marked significant milestones in the field of brine management technologies. These systems consistently produce the desired brine flow and concentration, significantly reducing the load on subsequent thermal evaporation processes. Notably, they achieve this with exceptionally low power consumption, enhancing overall energy efficiency and sustainability in industrial applications. Additionally, Hyrec OARO systems are adaptable to various operational environments, making them versatile solutions for challenging zero liquid discharge scenarios.

Thermal System

In the production of food-grade salt, thermal systems play a pivotal role in the efficient concentration and crystallization of salt from brine. Among the most effective and energy-efficient systems utilized in this process are the falling film evaporator and the forced circulation crystallizer, both of which can be optimized through the integration of mechanical vapor recompression (MVR) technology.

The system is engineered to generate 25.5 metric tons per hour of food-grade salt with a purity level exceeding 99.5% from raw brine using the previously described systems. The purification and crystallization of the salt are accomplished through a combination of a falling film evaporator and a forced circulation crystallizer. Both of these components are powered by two-stage mechanical vapor decompressors. This integrated approach ensures efficient and high-purity salt production, leveraging advanced technologies to optimize the purification process.

Falling Film Evaporator

The falling film evaporator is a widely used piece of equipment in the initial stages of salt production, where brine concentration is required. This evaporator operates by allowing the brine to flow as a thin film over vertically arranged tubes, while steam or another heating medium circulates around the exterior of these tubes. The design facilitates a high rate of heat transfer, enabling rapid evaporation of the water content from the brine.

One of the significant advantages of the falling film evaporator is its ability to operate at low temperatures and with minimal residence time, thus preserving the quality of the product. The thin film formed on the tubes ensures uniform heating, reducing the risk of fouling and allowing for the treatment of heat-sensitive materials. This is particularly important in food-grade salt production, where purity and quality are paramount.

Forced Circulation Crystallizer

Following the concentration stage, the saturated brine is typically transferred to a forced circulation crystallizer. This system is designed to induce supersaturation and promote the formation of salt crystals. In this process, the concentrated brine is circulated through a heat exchanger, where it is heated, before entering a crystallization chamber. Further evaporation within the chamber causes the salt to crystallize out of the solution.

The forced circulation crystallizer is highly effective in managing high-viscosity solutions and is capable of producing uniform, high-purity salt crystals. The system's design allows for continuous operation, ensuring a consistent and high- quality output, which is essential for meeting the stringent standards of food-grade salt production.

Mechanical Vapor Recompression (MVR)

To further enhance the energy efficiency of these thermal systems, MVR is employed. MVR technology works by compressing the vapor generated during the evaporation process, increasing its temperature and pressure, and then reusing it as a heating medium for the evaporator. This recycling of energy significantly reduces the need for external heat sources, making the process more sustainable and cost-effective.

Incorporating MVR into the operation of falling film evaporators and forced circulation crystallizers not only reduces operational costs but also minimizes the environmental impact of salt production. The integration of MVR ensures that the energy consumed in heating the brine is reused efficiently, thus lowering the overall energy footprint of the production process.

As a summary, the combination of falling film evaporators, forced circulation crystallizers, and MVR technology represents a highly efficient and sustainable approach to food-grade salt production. These systems work in tandem to concentrate brine, promote crystallization, and recycle energy, ensuring that the production process is both cost- effective and environmentally responsible.

Conclusion

Indonesia Desalination and Salt Production Plant represents a remarkable leap forward in its field. This plant has integrated cutting-edge technologies, including membrane-based systems such as SWNF, SWRO, and an innovative membrane-based brine concentration system. Especially, Hyrec's OARO system has set new benchmarks for efficiency and sustainability in resource management, making the plant a model for future projects.

We reinforce the criticality of a robust pretreatment upstream of the membrane systems to ensure the nanofiltration, in this case, the DK-440 membranes from Veolia, maintain optimal divalent/monovalent fractionation in the long term. The selection of the NF membrane must be based not only on the absolute divalent rejection, but as well on a high monovalent ion passage to avoid profit losses in the salt (NaCl) production and in necessary oversizing the equipment to compensate for these NaCl losses. The combination of a carefully thought-out design, experienced companies in the field, and state of the art membranes in operation from Hyrec and Veolia has proven to be an optimal choice for the reliability of performance and operation of the plant.

The plant's design ensures it maintains high operational efficiency even under diverse climatic conditions, which is particularly challenging given the fluctuating seawater characteristics between Indonesia's monsoon and dry seasons. The specific power consumption metrics highlight the plant's well-optimized energy usage, demonstrating that it consistently meets its production targets while minimizing its environmental footprint. This focus on energy efficiency is crucial for both economic viability and environmental sustainability.

In conclusion, the Indonesia Desalination and Salt Production Plant is not merely a showcase of current technological capabilities but a blueprint for the future of desalination and sustainable resource management. Through advanced technology and a commitment to environmental stewardship, this plant exemplifies how infrastructure can meet human needs while safeguarding the planet for future generations. The insights gained from its operation will undoubtedly shape the future of global desalination projects, contributing to broader efforts in sustainable resource management.

References

1. APHA. Standard Methods for the Examination of Water and Wastewater (23rd ed.). Washington DC: American Public Health Association. 2017