

DESIGN AND EVALUATION OF A SEAWATER REVERSE OSMOSIS DESALINATION PLANT USING COMPUTER SOFTWARE

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Abstract

Seawater and brackish desalination using reverse osmosis (RO) has been a pragmatic approach to mitigating fresh water shortage in many water-stressed areas worldwide. Compared with other desalination technologies, RO has several attributes including high energy efficiency and system modularization. To achieve these notable attributes, for large-scale seawater RO plants, it is critical to accurately design and evaluate the RO process before plant installation and operation. In this study, the IMSDesign software is applied to design a seawater RO plant with a capacity of 100 m³ of fresh water per hour. The software allows to customize the design parameters and operating conditions of the RO plant to meet the design requirements. After inputting design parameters and operating conditions, the RO plant operation can be simulated to obtain its performance indexes for plant design evaluation. The evaluation results reveal that the RO plant with membrane trains arranged in 2-passes configuration can obtain high quality permeate that meets the required standards for drinking water at energy consumption and water cost of 10.66 kWh/m³ and 2.48 USD/m³, respectively.

Keywords: *Reverse osmosis; seawater desalination; membrane technologies; IMSDesign software; fresh water supply.*

1. Introduction

Desalination of seawater and brackish water has been a practical solution to augmenting fresh water supply in many areas worldwide. According to a report from International Desalination Association (IDA), by February 2020, the global desalination market had reached a daily production of 97 million cubic meter, enabling secured fresh water supply to approximate 4% of the global population [1]. Moreover, the global desalination capacity is projected to increase steadily in coming years because of significant advancements in desalination technologies, particularly with the leading role

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of RO. Given its maturity, RO has helped to reduce the energy consumption and hence the operational cost of seawater desalination to as low as 2.6 kWh/m³ and 0.5 US\$/m³, respectively [2, 3]. The capital cost of RO systems has been also noticeably reduced in recent years due to the full commercialization of the technology. Beside RO, other emerging desalination processes including membrane distillation (MD), forward osmosis (FO) are promising to boost the global desalination capacity. In this context, desalination of seawater and brackish is now deemed a feasible approach to solving fresh water shortage in many water-stressed areas, including both developed and developing countries.

In recent years, there has been a paramount need for seawater and brackish water desalination in Vietnam due to the nationwide aggravated fresh water shortage caused by global warming and resultant climate change [4, 5]. Despite locating in a tropical region, climate change has distorted the weather patterns, leading to more frequent droughts and salt intrusion in many areas in Vietnam. Droughts and salt intrusion are expected to become even more severe in coming years, putting more pressure on secured fresh water supply in Vietnam [6]. Thus, research and development of desalination technologies including RO are considered one of the key strategies to secure fresh water supply and hence boost the economy of coastal areas and islands of Vietnam.

RO desalination achieves fresh water from saline water sources without the involvement of water evaporation and subsequent water vapor condensation as required in conventional thermal desalination technologies. Indeed, the RO desalination process relies on a semi-permeable membrane and a high-pressure pump to obtain fresh water (permeate) from a saline water feed [7, 8]. Given its selectivity, the semi-permeable RO membrane allows for the permeation of water molecules while retaining most dissolved salts and other contaminants in the feed stream. The transfer of water molecules across the RO membrane is driven by the transmembrane hydraulic pressure gradient, which is induced by the high-pressure feed pump. To enable the movement of water molecules from the saline feed to the permeate, this transmembrane hydraulic pressure is required to overcome the osmotic pressure of the feed. With these working principles, the key operating conditions of the RO desalination process are feed water salinity (i.e., or feed water osmotic pressure), feed pressure, and water recovery while the most important process performance indexes are salt rejection, water flux, and energy consumption.

Process design, evaluation, and optimization play a vital role in RO application for seawater and brackish water desalination. The properties of seawater and brackish water greatly vary between geological locations and seasons, thus leading to considerable variations in the performance indexes of various seawater/brackish water RO desalination plants worldwide [9]. The RO performance indexes are also profoundly affected by the plant design and operating parameters, including membrane nature, membrane module design (e.g., number of vessels and elements), system configuration (number of stages and passes), feed operating pressure, feed flow rate, and process water recovery [7]. It is important to note that the evaluation and optimization of a real large-scale RO desalination plant are unfeasible given the high operational cost and the complexity of the plant.

This work aims to design and evaluate a large-scale seawater RO desalination plant using a commercial computer software. Key design parameters and operating conditions of the seawater RO plant are considered, selected, and inputted into the software. The performance indexes of the RO plant when operating under the design parameters and conditions are obtained and analyzed. The ultimate purpose of this work is to provide a guideline to Vietnamese membrane engineers and scientists on design and operating a large-scale seawater RO desalination plant for fresh water supply.

2. Methodology

In this work, a seawater RO desalination plant with a capacity of 100 m³ fresh water per hour is designed using the IMSDesign software developed by Hydranautics. The abbreviation IMS stands for Integrated Membrane Solutions, and the IMSDesign software is destined for the design and evaluation of RO systems that use Hydranautics' membranes. As stated by the developer, the software is one of the most powerful tools that enable the quick and accurate design and analysis of the membrane-based water treatment systems. More importantly, the IMSDesign software is freely provided to membrane engineers and scientists at <https://membranes.com/solutions/software-imsdesign/>. The software is compatible with various Microsoft operating systems including Windows XP SP3, Windows 7, Windows 8, and Windows 10.

The seawater RO desalination plant is assumed to be installed on Ly Son Island, which belongs to Quang Ngai Province in Vietnam. On this island, seawater is easily accessed at beaches. With the capacity of 100 m³/h (i.e., equivalent to 2,400 m³/d with continuous operation), the plant is designed to meet the fresh water demand of approximately 6,400 residents (i.e., which is one third population of Ly Son district).

3. Results and discussions

3.1. Characteristics of the seawater feed into the RO plant

The characteristics of the raw seawater sampled at a beach on Ly Son Island [10] are used as the inputs to the RO plant design. Before being fed to the RO plant, the raw seawater is pre-treated using a conventional method (i.e., coagulation followed by media filtration). Of a particular note, the raw seawater has pH of 7.8, posing a considerable threat of scale formation on the membrane surface in RO membrane modules. Therefore, pH adjustment is conducted by dosing acid sulfuric (H_2SO_4) into the feed water prior to the RO membrane modules. The software allows for the calculation of the characteristics and element compositions of the pre-treated RO feed water. The characteristics of the raw seawater and the pre-treated seawater feed are provided in Table 1.

Table 1. Characteristics of the raw seawater and the pre-treated seawater feed into the RO process

	Raw seawater feed	Pre-treated seawater feed
<i>General characteristics</i>		
pH	7.8	7.2
Total dissolved solids (TDS), mg/L	33,810	29,689
Osmotic pressure, bar	25.7	22.5
Electrical conductivity, $\mu S/cm$	53,232	47,086
<i>Elemental compositions (mg/L)</i>		
Calcium	400	350
Magnesium	1,090	953
Sodium	10,800	9,488
Potassium	390	343
Ammonia	0.1	0.09
Bicarbonate	0.1	0.09
Sulfate	904	793
Chloride	20,212	17,746
Nitrate	0.05	0.04
Boron	4.5	4.3

3.2. Design of the seawater RO desalination plant

The seawater RO desalination plant is designed to achieve an operating capacity of 100 m³ fresh water per hour. The overall process of the RO plant is shown in Fig. 1. The core section of the plant is RO desalination membrane vessels. In this design, the RO membrane vessels are arranged into 3 identical trains, each of them has an operating capacity of ~ 50 m³/h. During a normal operation, two trains are operated to produce

100 m³/h of fresh water, while one train is in standby mode and used as a preserved one. This preserved train will be used in case of technical problems or/and membrane cleaning that cause the termination of other train(s). It is necessary to emphasize that the capacity of RO membrane trains and vessels depends not only on the configuration/arrangement of membrane trains and vessels but also on operating conditions (e.g., feed flow rate, feed pressure, and water recovery). These operating conditions determine the water flux of RO membrane and hence the flowrate of the permeate (i.e., the desalinated fresh water from the RO vessels and trains).

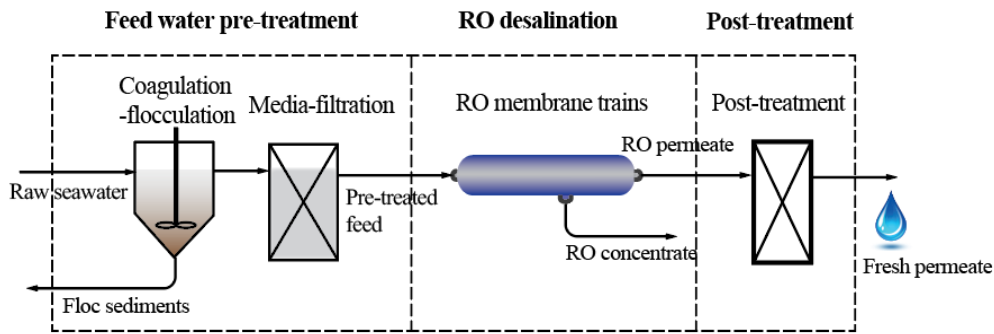
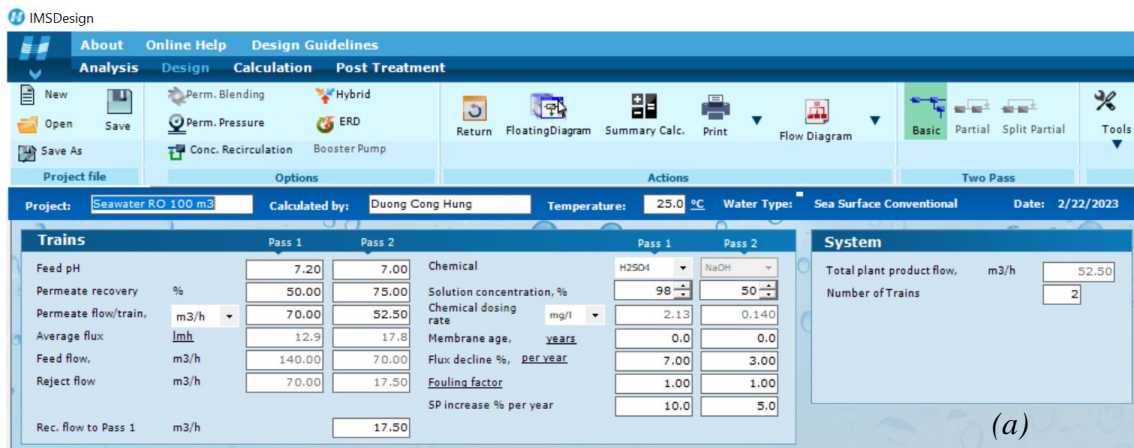


Fig. 1. The overall process of the seawater RO desalination plant designed with a capacity of 100 m³/h.

Given the abovementioned assumptions, the task to design the RO desalination section can be considered for one train. The IMSDesign software allows users to customize the design of RO membrane trains by setting up the number of trains, number of passes or stages, and operating conditions of each stage or pass (Fig. 2a). As conventional rules in RO design, staging RO membrane vessels is applied to increase the process water recovery as retentate (i.e., also termed concentrate or brine) from one stage is fed to the next one for further treatment. On the other hand, in multi-passes arrangement, permeate from one pass is further treated in the next one, thus enhancing the quality of the product water but reducing the process water recovery. Depending on various factors, multi-stages or multi-passes arrangement is selected for the RO desalination section.

One critical parameter that needs to be considered during the design of the RO trains is the quality of the permeate. RO membranes are highly selective to water molecules, but they cannot completely retain all contaminants, particularly ones with small molecular sizes such as boron (B). Most commercial RO membranes can reject up to 99.9% of dissolved salts, but their boron removal rates are much lower and highly vary from 73% to 90% [11, 12]. Indeed, boron removal rates of RO membranes are profoundly affected by both the membrane nature and the pH/temperature of feed

water [11, 12]. Given its mounting health concern, maximum allowable limits on boron concentration in fresh water and drinking water have been imposed by environmental protection agency (EPA) of many countries in the world. For example, some states in USA have regulated the maximum allowable boron concentration in drinking water as low as 0.5 mg/L to 1.0 mg/L [13]. Vietnam has not regulated boron concentration in fresh water and drinking water. However, for the safety of end users, the seawater RO desalination plant is designed to achieve product water with boron content ≤ 1 mg/L.



2-passes RO membrane train

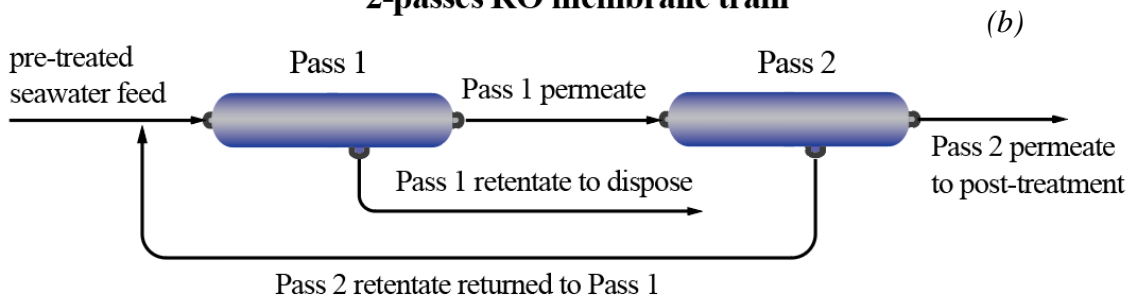


Fig. 2. (a) Design parameters of one RO train and (b) the schematic diagram of a 2-passes RO membrane train.

With properties of the raw seawater and the pre-treated feed shown in Table 1, single-pass RO filtration can not meet the requirement on permeate quality regarding boron content. Regardless of selected membrane types, the single-pass RO train fails to bring boron concentration in the permeate to ≤ 1 mg/L. As a result, two-passes membrane trains are selected for the seawater RO desalination plant designed in this work. With this arrangement, the permeate from the first RO membrane arrays is fed to the subsequent arrays; therefore, concentrations of contaminants including boron in the permeate obtained from the RO membrane train are noticeably reduced (Fig. 2b).

Choosing proper membrane elements used in the membrane trains is critical to the design of the seawater RO desalination plant. The IMSDesign software offers a library which contains all membrane element types provided by Hydranautics (Fig. 3). From the library, software users can select the most suitable membrane element types for the plant design requirements. Currently, Hydranautics offers various membrane elements in the two most common sizes (e.g., 4 × 40 inch and 8 × 40 inch) for seawater and brackish water RO plants. Of a particular note, these membrane elements differ in nominal production (i.e., membrane water flux or permeate flow), required feed pressure, and salt rejection (Fig. 3).

	Model	Nominal production (gpd)	Salt rejection, %	Element type	Size (in x in)	Area (sq.ft)	Spacer (mil)	Test pressure (psi)	Feed pressure (bar)	Permeate TDS (mg/l)
C	ESPA2-LD	10000	99.60	BWRO Low Pressure High ...	8 X 40	400	34	150		
C	ESPA2-LD MAX	12000	99.60	BWRO Low Pressure High ...	8 X 40	440	34	150		
C	ESPA4 MAX	13200	99.20	BWRO Lowest Pressure	8 X 40	440	28	100		
C	ESPA4-LD	12000	99.20	BWRO Lowest Pressure Lo...	8 X 40	400	34	100		
C	ESPA4-LD HP	11000	99.20	BWRO Lowest Pressure Lo...	8 X 40	400	34	100		
C	ESPAB MAX	9000	99.30	BWRO Low Pressure Boron...	8 X 40	440	28	150		
C	LFC3-LD	11000	99.70	BWRO Low Fouling High Re...	8 X 40	400	34	225		
C	SWC4 MAX	7200	99.80	SWRO Highest Rejection	8 X 40	440	28	800		
C	SWC4-LD	6500	99.80	SWRO High Rejection Low ...	8 X 40	400	34	800		
C	SWC5 MAX	9900	99.80	SWRO High Rejection	8 X 40	440	28	800		
C	SWC5-LD	9000	99.80	SWRO High Rejection Low ...	8 X 40	400	34	800		
C	SWC6 MAX	6600	99.60	SWRO Highest Flow	8 X 40	440	28	600		
C	SWC6-LD	6000	99.60	SWRO High Flow Low Dp	8 X 40	400	34	600		
C	SanRO-HS2-4...	3000	99.60	Sanitary Highest Flow	4 X 40	90	32	225		
C	SanRO-HS-4	2200	99.70	Sanitary High Rejection	4 X 40	90	32	225		

Fig. 3. The pop-up window allowing for selecting suitable membrane elements for the seawater RO plant.

The 3 membrane trains used in the seawater RO desalination plant are arranged in 2-passes configuration. In this arrangement, the pre-treated seawater is fed to the first pass (Pass 1), and the permeate from the first pass is introduced to the second pass (Pass 2). The significant differences in the properties of feed water to Pass 1 and Pass 2 require different membrane element types for them. The SWC5 MAX membrane elements are chosen for Pass 1 to achieve high salt rejection, whereas ESPAB MAX type (i.e., brackish water low pressure boron removal) is selected for Pass 2 to guarantee its permeate boron content ≤ 1 mg/L (Fig. 4).

In addition to membrane element types, the RO membrane train designer needs to decide the number of elements per vessel and the number of vessels in each pass of the RO membrane train. One RO membrane vessel might contain up to 8 elements in series.

In one vessel, the retentate from one element is fed to the following one in the series. With this arrangement, a vessel with more elements can achieve a higher water recovery but requires a higher feed operating pressure. Thus, the selection of number of elements in a vessel is a trade-off between water recovery and feed operating pressure (i.e., and hence energy consumption). There is a consensus that the RO desalination process with seawater feed is operated at low water recovery to prevent membrane scaling caused by sparingly soluble salts (e.g., calcium sulfate and calcium phosphate). With this consensus, RO membrane vessels with 6 elements are selected for the seawater RO desalination plant (Fig. 4).

Number of vessels used in each pass of the RO membrane train is determined based on the average water flux at which the pass is operated. Given the input values of permeate recovery and permeate flow, the average flux of Pass 1 and Pass 2 is inversely proportional to their number of vessels. In other words, the pass is operated at lower average flux when more vessels are used. The IMSDesign software allows the user to input the number of vessels in each pass (Fig. 4) then it automatically calculates the average flux based on the selected membrane element type, feed water salinity, and the targeted permeate flow.

		Pass 1	Pass 2			Pass 1	Pass 2
Feed pH		7.20	7.00	Chemical		NaOH	
Permeate recovery	%	50.00	75.00	Solution concentration, %	98	50	
Permeate flow/train,	m3/h	70.00	52.50	Chemical dosing rate	0.000	0.000	
Average flux	lmh	12.9	17.8	Membrane age, years	0.0	0.0	
Feed flow,	m3/h	140.00	70.00	Flux decline %, per year	7.00	3.00	
Reject flow	m3/h	70.00	17.50	Fouling factor	1.00	1.00	
Rec. flow to Pass 1	m3/h		17.50	SP increase % per year	10.0	5.0	

		Stage 1	Stages
Element type		SWCS MAX	Pass 1: 1
Elements / Vessel		6	
No. of Vessels		22	

		Stage 1	Stages
Element type		ESPAB MAX	Pass 2: 1
Elements / Vessel		6	
No. of Vessels		12	

Fig. 4. Design parameters of one RO train.

3.3. Evaluation the performance of the seawater RO desalination plant

The performance of the seawater RO desalination plant is evaluated under the design parameters and operating conditions listed in Table 2. Of a particular note, Pass 1 and Pass 2 are operated at water recovery rate of 50% and 75%, respectively, when considering the membrane fouling propensity of their feed water. The permeate flow of Pass 2 is 52.5 m³/h, which is also the permeate flow of the RO membrane train. At water recovery of 50% and 75%, the feed flow to Pass 1 and Pass 2 is 140 m³/h and 70 m³/h, respectively. The retentate from Pass 2 at the flow rate of 17.5 m³/h is returned to and blended with the feed water of Pass 1. When operating at these permeate flow and water recovery, the average flux of Pass 1 and Pass 2 is maintained at 12.9 L/m².h and 17.8 L/m².h when they use 22 and 12 vessels, respectively. The average flux of Pass 1 is deliberately maintained lower than that of Pass 2 due to the significantly higher membrane fouling/scaling propensity of the pre-treated seawater compared to the Pass 1 permeate. It is well-established that membrane fouling/scaling during the RO process is exacerbated when operating at higher water flux [14].

Table 2. Design parameters and operating conditions of Pass 1 and Pass 2 of the RO membrane train with a capacity of 52.5 m³/h.

Design parameters and operating conditions	Pass 1	Pass 2
Membrane element type	SWC5 MAX	ESPAB MAX
Number of elements per vessel	6	6
Number of vessels	22	12
Water recovery, %	50	75
Permeate flow, m ³ /h	70	52.5
Feed flow, m ³ /h	140	70
Reject flow, m ³ /h	70	17.5
Feed pressure, bar	47.6	5.2
Average flux, L/m ² .h	12.9	17.8

With these design parameters and operating conditions, Pass 1 obtains permeate meeting requirements for fresh water used for sanitation. As demonstrated in Table 3, Pass 1 permeate has total dissolved solids (TDS) and electrical conductivity of 210 mg/L and 451 μ S/cm, respectively, and low concentrations of dissolved salts. However, the boron content of Pass 1 permeate is 1.5 mg/L, which is noticeably higher than the designed maximum allowable content (1 mg/L). The excessive boron content of Pass 1 permeate requires it to be further treated in Pass 2. Indeed, permeate obtained

from Pass 2 exhibits negligible dissolved salts contents (i.e., TDS of 5.5 mg/L and electrical conductivity of 10.6 $\mu\text{S}/\text{cm}$) and particularly a boron concentration of 0.9 mg/L. Low pH (i.e., 5.6) and ion concentrations of Pass 2 permeate induce its post-treatment necessary prior to supply to end users for drinking purpose.

Other critical performance indexes of the seawater RO desalination plant are the energy consumption and water production cost. As shown in Table 2, the feed pressure applied for Pass 1 and Pass 2 is 47.6 bar and 5.2 bar, respectively. This high pressure together with high flow rate require large high-pressure feed pumps, and pumping is the dominant factor contributing the to overall energy consumption of the RO desalination plant. When operating at conditions listed on Table 2, the pumping energy of the seawater RO desalination plant is 10.66 kWh/m³, which is consistent with the reported energy consumptions of seawater RO desalination plants in the literature. Furthermore, when considering all factors affecting the investment and operational expense, the water production cost of seawater RO desalination plant is 2.48 USD/m³.

Table 3. Characteristics of the permeate from the Pass 1 and Pass 2 of the RO membrane trains. In these trains, permeate from the Pass 1 is fed to the Pass 2 for further treatment. Feed pH adjustment is applied prior to Pass 1 (pH = 7.2) and Pass 2 (pH = 7.0) by dosing sulfuric acid and sodium hydroxide solution, respectively.

	Pass 1 permeate	Pass 2 permeate
General characteristics		
pH	5.8	5.6
Total dissolved solids (TDS), mg/L	210	5.5
Osmotic pressure, bar	0.2	0
Electrical conductivity, $\mu\text{S}/\text{cm}$	451	10.6
Elemental compositions (mg/L)		
Calcium	0.03	0
Magnesium	0.08	0
Sodium	79.0	1.7
Potassium	3.6	0.1
Ammonia	0	0
Bicarbonate	0	0
Sulfate	1.4	0
Chloride	125	2.7
Nitrate	0	0
Boron	1.5	0.9

4. Conclusions

In this study, the IMSDesign software is used to design and evaluate a seawater RO desalination plant with a capacity of 100 m³ fresh water/h. The flexibility of the software allows for quick and accurate design and evaluation of the RO plant. The simulated results demonstrate that the seawater RO plant consisting of 3 identical membrane trains can sufficiently produce 100 m³/h of water product that meet standards for drinking water. Each membrane train is arranged in 2-passes configuration whereby the permeate from Pass 1 is fed to Pass 2 for improved quality of the water product. Equipped with 22 and 12 vessels (i.e., each vessel contains 6 membrane elements), Pass 1 and Pass 2 exhibit average water flux of 12.9 L/m².h and 17.8 L/m².h when operating at water recovery of 50% and 75%, respectively. With these design parameters and operating conditions, the seawater RO desalination plant demonstrates pumping energy and overall water cost of 10.66 kWh/m³ and 2.48 USD/m³, respectively.

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THIẾT KẾ VÀ ĐÁNH GIÁ HỆ THỐNG LỌC NƯỚC BIỂN RO SỬ DỤNG PHẦN MỀM MÁY TÍNH

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Tóm tắt: Khử mặn nước biển và nước lợ sử dụng công nghệ thẩm thấu ngược RO đã là một giải pháp hiệu quả để giải quyết vấn đề khan hiếm nước ngọt ở nhiều nơi trên thế giới. So với các công nghệ khử mặn khác, công nghệ RO có những ưu điểm nổi trội, đặc biệt là có hiệu suất năng lượng cao và khả năng mô đun hóa hệ thống. Để đạt được những ưu điểm này, đối với các nhà máy lọc nước biển có quy mô lớn, việc thiết kế và đánh giá chính xác hệ thống trước khi xây dựng và vận hành có ý nghĩa rất quan trọng. Trong nghiên cứu này, phần mềm IMSDesign được sử dụng để thiết kế một nhà máy lọc nước biển RO với công suất 100 m³ nước sạch/giờ. Phần mềm này cho phép chọn lựa và cài đặt các thông số thiết kế và vận hành nhà máy RO để đáp ứng được các tiêu chí thiết kế. Sau khi nhập các thông số thiết kế và vận hành, hoạt động của hệ thống RO được mô phỏng để thu được các thông số hoạt động để đánh giá việc thiết kế nhà máy. Các kết quả khảo sát cho thấy rằng hệ thống RO với các khối màng lọc được bố trí theo cấu hình 2 lần lọc thu được nước lọc có độ tinh khiết cao, đáp ứng các tiêu chuẩn cho nước uống với năng lượng tiêu thụ và giá thành nước lọc lần lượt là 10,66 kWh/m³ và 2,48 USD/m³.

Từ khóa: Thẩm thấu ngược; khử mặn nước biển, công nghệ màng, phần mềm IMSDesign; cung cấp nước sạch.

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