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Design of Reverse Osmosis Desalination Plant in Suez City (Case Study)

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Abstract Water shortage is an important issue facing the world today. Due to the increasing demands of fresh water in deserted and remote areas, the development of non-conventional water resources in Egypt is essential. A case study for a 3000 m³ permeates/day RO desalination plant in Ain El Sokhna-Suez, Egypt is reviewed and analyzed. According to the plant location and site characteristics, several considerations have been evaluated in the design of the RO desalination plant. The Design of the plant has been adopted using ROSA software as well as basic design equations for RO system design. Detailed economic study has been adopted to evaluate the feasibility of the plant. The cost calculations of the RO plant indicated that the main factors which affect the cost of the produced water are membrane cost and the power consumption cost, whereas the chemical treatment represents almost 10% of the total cost.

Keywords Desalination, Case Study, reverse osmosis, economic study, design.

Introduction

Fresh water shortage nowadays becomes a major problem in many coastal areas. Seawater desalination is used for providing fresh water aimed at both domestic and industrial usage. There are two main methods dominating the desalination process technologies, thermal and membrane-based process. The thermal desalination process has the advantage of using without complicated pre-treatment, nonetheless. It has a disadvantage of high energy consumption. Currently, there is a growing demand on using membrane based seawater desalination technology [1].

Choosing an appropriate seawater pretreatment system is mandatory for providing feed water with low turbidity for the reverse osmosis desalination process. Ultrafiltration membranes used to remove particles, virus, bacteria, moreover eliminating colloidal substance and they are more reliable in producing RO feed water with low fouling potential than using the conventional pre-treatment techniques even through destructive algal blooms event [2].

The process of water recovery of seawater using reverse osmosis (SWRO) desalination process ranged between 30% and 40% [3], and there is an important design parameter which determine the size and cost of SWRO desalination system. Nevertheless, the increase of water recovery possibly causes scaling inorganic substances on membrane surface and therefore SWRO systems will require abundant regular membrane cleaning and this may lead to short membrane life and membrane replacement [4-5]. Hence, increasing the water recovery of SWRO process while evading membrane scaling has become a significant goal. Shammiri and Dawas [6] found that when reducing the feed water pH from 7.2 to 7.0, even if no scale inhibitor has been added, the water recovery of SWRO plant has been improved from 22.5% to 34.2%, without any damage to the membrane surface due to scaling. Kurihara and coworkers [7-9] designed a brine conversion system (BCS) consists of two stages for SWRO desalination process where an 60% overall water recovery has been attained. Kim et al. [10] designed a multistage RO system for the desalination of seawater on 5 m³/h pilot plant using micro-filtration as a pre-treatment technique, the results showed that the water recovery successfully increased from 30% up to 50%.

The main issue in desalination technologies, either membrane or thermal, is the energy cost as these processes are energy intensive. In the attempt to reduce operating cost, RO systems with large scale are nowadays equipped to improve the mechanical compression energy from the discharged concentrated brine stream [11].



Pre-treatment is a main concern to protect the membrane in the RO plant, therefore the feed water should be well pre-treated. The design of pretreatment system depends on different factors, such as the composition of seawater and physical properties, water intake, membrane materials, and the recovery ratio [12].

RO desalination cost may be divided into three main parts: direct capital cost, indirect capital cost, and annual operating cost. Direct capital costs comprise land cost, buildings, and equipment, while the construction overheads, eventuality costs and insurance are considered as an indirect capital costs. Furthermore, the annual operating costs include energy, maintenance, chemicals, expenses etc. A wide distribution of these cost items are widely reported [13].

Electricity consumption of SWRO plants ranged between 4 and 7 kWh/m³, depending on many factors as: "salinity of seawater", "recovery ratio", "permeate quality", plant outline and the usage of energy recovery system in the brine blowdown [14]. Lamei et al, (2008) estimated the "unit production cost" in Egypt compared to worldwide cost [15]. The unit production cost for different plants in Egypt, KSA and Cyprus has been also estimated.

Obaidani et al [16] studied the membrane distillation by performed energy analysis, a study and economical assessment have been done for evaluating the feasibility of direct contact membrane distillation (DCMD) process with heat retrieval. In this research water cost has been estimated to be \$1.17/m³, which is analogous to the cost produced by conventional thermal system, for example: \$1.40/m³ for MSF and \$1.00/m³ for MED [17]. The study also displayed that there is a high opportunity for reducing the costs incase of using a low-grade thermal energy source. In another study, it was showed that the calculated cost is competitive to the cost of water produced by RO, which is about \$0.5/m³ [18-19].

In the current study, RO desalination plant with a medium-capacity of 3000 m³ permeate/day has been used to supply fresh water for a community in Suez city Ain El-sokhna (case study).

Case Study Design and Operating Parameters

Design Operating Conditions

According to the plant location and site characteristics, several considerations have been evaluated to design a 3000 m³/day RO desalination plant. Design basis and operating conditions are mentioned in Table1. Applying ROSA software as well as basic design equations for RO system design.

Table 1: Design basis and Operating Conditions of the RO desalination system

Operating Pressure	15.3 bar
Raw water temperature	30 °C
Raw water TDS	7000 ppm
Product water line pressure	1 bar
Recovery ratio	65%
Applied pressure for RO element	15.30 bar
Recovery ratio	60-65%
Water classification well water	SDI < 3
Feed water pH	7.6
Chemical Dosing Ratio:	
Sodium Hypochlorite	3 ppm
Anti-scalant	3 ppm
SBS (sodium bi sulfite)	9-15 ppm
Sodium Hypo chlorite for product	1.5 ppm
Caustic Soda	20 ppm
Sulfuric Acid	45 ppm

All chemicals in table are 100% concentration.

Operating Requirement

Electrical energy consumed/m³ of permeate is assumed to be 1.715 kWh for water capacity of 230 m³/hr. Chemical cleaning is required for cleaning membrane elements according to the degree of fouling and/or drop of permeate output. Cleaning chemicals which may be used as required are mentioned below:

- Citric Acid
- Hydraulic Acid, HCl
- Caustic Soda
- Sodium Sulfate
- E.D.T.A



Performance Calculation of a Reverse Osmosis Unit

The quantity of water produced by a reverse osmosis unit can be given approximately by the following formula:

$$D_p = A \cdot (P_A - P_{osm} - P_p) \quad (1)$$

Where:

D_p product water flow rate expressed in m³/hr

A coefficient related among other things to temperature

P_A operating pressure also called applied pressure on the module expressed in bar.

P_{osm} average osmosis pressure of the solution inside the module (bar)

The average pressure is calculated taking into account the average concentration of salts in the raw water as well as of the recovery rate. P_p is the pressure in the product water line (bar). The nominal flow for the unit has been calculated on the design basis and estimated operating conditions.

Materials and Methods

Process Flow Diagram

Process flow diagram for the brackish desalination plant is indicated in Fig 1. The RO desalination plant consists of a pretreatment system, RO desalination system, a post treatment system and other facilities (such as product water storage tank, brine blow tank ...etc.)

Pretreatment System

This system is designed for the desalination of well water with a capacity of 3000 m³/d. It is important to note that the system installed can protect, in a reliable way, the modules of the reverse osmosis unit which, are the most important parts as well as the most costly part in this plant. Fluctuations of feed water quality leads to a proper design of the reverse osmosis unit as well as the pretreatment have to be correctly designed. In such a case the possibility of accidental fouling of modules cannot be excluded. It is essential to take proper actions, such as cleaning, disinfecting and rinsing. The lifetime of the modules depends on the daily/weekly control routines as well as upon the attention. The pretreatment system consists of:

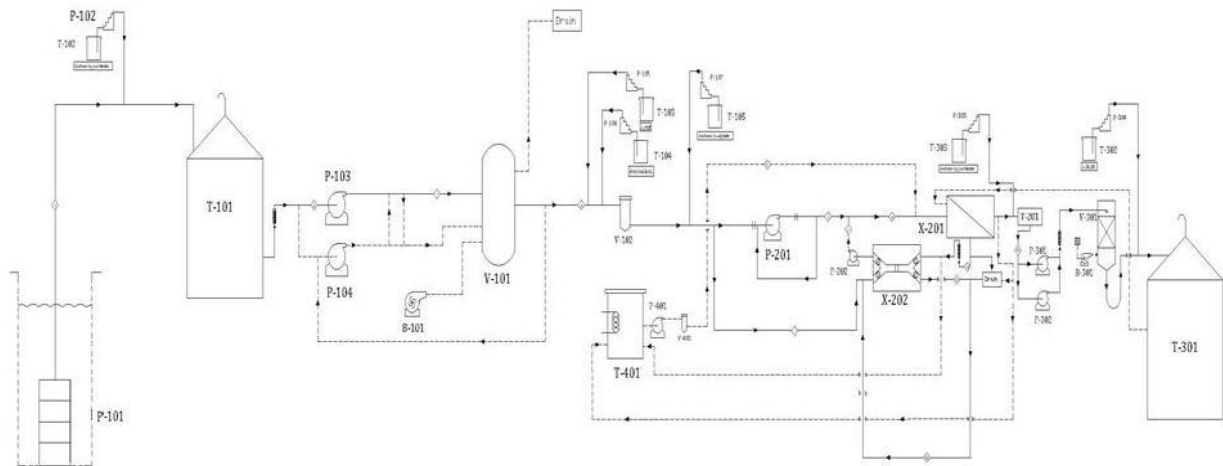


Figure 1: A "Process Flow Diagram" of RO Desalination Plant in Suez City

Disinfection of raw water

Raw water pumped up from wells is disinfected by sodium hypochlorite (NaClO) injection, and the sterilized water is stored in a raw water storage tank. Chlorine disinfection is used as it deactivates most pathogenic microorganisms quickly. Chlorination is regularly used where biological-fouling anticipation is needed.

Filtration

Disinfected water is pumped to multimedia filters through multimedia filter feed pumps; to reduce the SDI (silt density index) value of the feed water stream, normally coagulant is added to the stream of raw water and effectively mixed. The process of coagulant rapid dispersion and mixing is tremendously important, so that in line static mixer has been associated for that reason. The formed micro flocs are immediately removed using media filtration. In line filtration can be used for the raw water stream with a SDI only slightly above 5.



Multimedia filters

By means of a well-designed and operated multimedia filter, SDI of less than 5 can normally be attained. The most common filter media in water treatment are sand and anthracite. For pressure filtration the filter vessels have been designed for pressurization; a higher-pressure drop can be used to a higher filter bed and/or higher filtration rates and/or smaller filter grains. During service, water to be filtered usually pass in the filter upper side, percolates over the filter bed, and it strained of through the collector system at the bottom. Occasionally, when the differential pressure between the inlet and outlet rinsed to overcome the deposited matter. Scale formation may cause the permeate flow rate to decrease, and it may cause the concentrate pressure to decrease. Fouling or scale formation can usually be prevented with the proper RO pretreatment.

pH Adjustment Acid Dosing Set

Since the solubility of CaCO_3 depends on the pH, by adding acid, the equilibrium can be moved to the left side of the chemical equation in order to keep the CaCO_3 dissolved in solution. To control the scaling of the calcium carbonate by acid addition only, the stiff and Davis stability index in the concentrate stream must be negative.

Scale Inhibitor-dosing Unit

Scaling of the membrane can occur when the concentration of the oppositely- charged ionic components of a dissolved salt exceed their solubility. At this point, a scale inhibitor is dosed in line of the process to decrease the possibility of scale formation.

De-chlorination Dosing Unit

The rate of chlorine dose relays on different feed water features. Sodium bisulfate is most commonly known compound used for the elimination of free chlorine and as a biostatic agent as RO feed must be dechlorinated to avoid membranes' oxidation.

Five Cartridge Filter

A cartridge filter with a pore size of 5 microns is required for every RO pretreatment system. Filtered water is forced to a five-micron multimedia filter. Usually it is the last step in the pretreatment sequence. The cartridge filters are equipped with a pressure gauge and a differential pressure transmitter to specify the differential pressure drop, thus indicating the amount of its fouling. Regular check the used cartridges provides useful data regarding fouling risk and clearing necessities.

RO Desalination System

The RO desalination system is designed using ROSA software. Thin film composite spiral wound membranes configuration is utilized in the RO unit. Dow Filmtec Type BW30-400, is selected as his membrane has lower replacement cost, simplicity in plumbing system, and easy maintenance. The elements are housed in FRP construction pressure vessels rated at a design pressure of 450 PSI.

An LPT 500 turbo charger is used to provide a boost pressure to a second stage permeate. The feed flows from the high pressure pump at a rate of $230.75 \text{ m}^3/\text{hr}$ at 14.04 bars to the first stage RO module. 1st stage permeate flow at $93.91 \text{ m}^3/\text{hr}$ and brine of $136.84 \text{ m}^3/\text{hr}$ at 12.79 bar is forced by the turbocharged to the 2nd stage module at pressure of 17.45 bar producing $56.06 \text{ m}^3/\text{hr}$ permeate and a brine of $80.78 \text{ m}^3/\text{hr}$ at a pressure of 16.40 bar, then flowing to the turbine side of the final brine blow down of $80.78 \text{ m}^3/\text{hr}$ will be discharged at 0.35 bar.

The first array pressure vessels are 20 and the second array vessels are 10, where 6 elements are included in each pressure vessel. About 65% of the feed water permeates through RO element and become product water. Total dissolved solids (TDS) of product water are less than 100 ppm. Concentrated water from RO unit is rejected to a 50 m^3 - brine tank.

Optional Post Treatment

Sodium hydroxide is injected to adjust the pH of the permeate water from the reverse osmosis to the set pH value. Chlorine has been used also for the disinfections of portable water where a remaining chlorine concentration around 0.5 mg/L is required. An optional degasified tower is provided to reduce the carbon dioxide in the product water, which was developed during the addition of the acid in the feed water. The degasified raises the product water pH thereby reducing the post pH adjusting chemical consumption. The use of the degasified also prevents any increase in the product TDS due to injection of more pH adjustment chemicals.



Results and Discussion

Design Calculation

By using ROSA software to design the desalination system, the following design calculations have been performed.

$$Q_{\text{element}} = 40 \text{ m}^3/\text{day}$$

$$\text{Recovery (assumed in ROSA trial)} = 60\%$$

$$Q_{\text{permeate}} = 3000 \text{ m}^3/\text{day (required to achieve)}$$

$$Q_{\text{feed (Calculated)}} = 5000 \text{ m}^3/\text{day}$$

$$\therefore \text{Number of elements} = \frac{5000}{40} = 125 \text{ element}$$

For safety reasons we decided that only 6 elements in each vessel

$$\therefore \text{Number of vessels} = \frac{125}{6} = 20.33333 \approx 21 \text{ vessel}$$

$$\text{Flux(permeate)} = \frac{3000}{37 * 125} = 0.648648$$

Pumps

$$\text{Vapor pressure at operating temperature} = 0 \text{ kg/cm}^2 \text{ a} = \text{bar}$$

$$\text{Normal flow rate} = 5000 \text{ m}^3/\text{day} = 208.3 \text{ m}^3/\text{h}$$

$$\begin{aligned} \text{Rated flow} &= \text{Normal flow} \times k \\ &= 208.3 \times 1.1 = 229.13 \text{ m}^3/\text{h} \end{aligned}$$

Where:

$$k; \text{ Safety factor} = 1.1$$

$$\text{Operating pressure} = 4.5 \text{ kg/cm}^2 \text{ a}$$

$$\text{Static suction head} = 0 \text{ m}$$

$$\text{Suction line friction loss } (\Delta P_f)$$

$$\Delta P_f = 1.5 \text{ kg/cm}^2 \text{ a}$$

$$\begin{aligned} \text{Pump suction pressure} &= \text{Operating pressure} + \text{Static head} - \text{Suction line friction loss} \\ &= 4.5 + 0 - 1.5 = 3 \text{ kg/cm}^2 \text{ a} \end{aligned}$$

$$\begin{aligned} \text{NPSHA} &= (\text{Operating pressure} - \text{Vapor pressure}) + (H_2 - H_1)_{\text{suc}} - (\Delta P_f)_{\text{suc}} \\ &= (4.5 - 0) + (0) - 1.5 = 3 \text{ kg/cm}^2 \end{aligned}$$

$$= \frac{3 \frac{\text{kg}}{\text{cm}^2} \times 10}{\text{sp.gr}} = \frac{3 \times 10}{1} = 30 \text{ m}$$

$$\text{NPSHR} < \text{NPSHA}$$

$$P < P_v$$

$$\text{Pressure at delivery} = 18.5 \text{ kg/cm}^2 \text{ a}$$

$$\text{Static discharge head} = 2 \text{ m} = (2 \times 1)/10 = 0.2 \text{ kg/cm}^2$$

$$\text{Discharge line friction loss} = 0.1 \text{ kg/cm}^2$$

$$\text{Filter pressure drop} = 0$$

$$\text{Furnace pressure drop} = 0$$

$$\text{Flow element pressure drop} = 0$$

$$\text{Misc. devices pressure drop} = 0$$

$$\text{Control valve pressure drop} = 0$$

$$\text{Pump discharge pressure} = 18.5 + 0.2 + 0.1 + 0 + 0 + 0 + 0 + 0 = 18.8$$

$$\begin{aligned} \text{Pump differential pressure} &= \text{pump discharge pressure} - \text{pump suction pressure} \\ &= (18.8 - 3) = 15.8 \text{ kg/cm}^2 \end{aligned}$$

$$\text{Pump differential head} = (15.8 \times 10) / 1 = 158 \text{ m}$$

$$\text{Max suction pressure} = \text{HHLL in suction tank} + \text{Design pressure (set of PSV)}$$

$$\text{HHLL} = 40 \text{ m}$$

$$\text{HHLL in suction tank} = (40 \times 1) / 10 = 4 \text{ kg/cm}^2 \text{ a}$$

$$\text{Max suction pressure} = 4 + 0 = 4 \text{ kg/cm}^2 \text{ a}$$

$$\text{Max Differential pressure} = \text{Safety factor} \times \text{Pump differential pressure}$$

$$\text{Take 20\% overdesign (Safety)}$$

$$\text{Max Differential pressure} = 1.2 \times 15.8 = 18.96 \text{ kg/cm}^2$$

$$\text{Max discharge pressure} = \text{Max suction pressure} + \text{Max differential pressure}$$

$$\text{Max discharge pressure} = 4 + 18.96 = 22.96 \text{ kg/cm}^2 \text{ a}$$



Pressure Exchanger (PX) - Cost saved:Concentrate pressure = $18.45 \times 1.1 = 20.3$ bar

Efficiency of "PX" = 96%

Permeate pressure after PX = 19.5 bar

Booster pump pressure = 3 bar to rise the pressure to 22 bar

Feed water to "PX flow rate" = $50\% \times 5000 = 2500 \text{ m}^3/\text{day}$

For high pressure pump $P_{\text{fluid}} = \rho g Q h_p$
 $= 1010 \times 9.81 \times 0.06 \times 204$
 $= 121275 \text{ watt} = 121.28 \text{ K watt}$

K watt/h = \$ 0.0416

Cost/day = $121.28 \times 0.0416 \times 24$

= \$ 121.1

Cost/year = \$ 44201.5

PX saved = \$ 44201.5 / 2 (for two streams)

= \$ 22100.75

Economic Study

In order to assess precisely the designed RO system, an economic analysis is vital. The study has been done for a (3000 m³/day). In addition to the capital cost, the major factors that influence the cost have found to be the power consumption, running and maintenance costs are also evaluated as stated in tables 2-4.

Calculations Methodology

For reverse osmosis plant, the calculations are as follows.

1. Amortization factor: $a = i * (1+i)^n / (1+i)^n - 1$
(n): plant life, (i): interest rate.
2. Annual fixed charges: (a)*(DC)
3. Annual electric power: (c)(w)(f)(m)(365)
4. Annual chemical cost: (k)(f)(m)(365)
5. Annual labor cost: (l)(m)(365)
6. Annual membrane replacement cost: (0.33) (membrane cost)
7. Total annual cost: 2+3+4+5+6
8. Unit product cost: (total annual cost)/(f)(m)(365)
9. Unit product cost: (total annual cost)/(m).

Where:

Direct capital cost: DC (\$)
 Plant capacity: m (m³/day)
 Electric cost: c (\$/kWh)
 Specific electric power: w (kWh/m³)
 Operating labor: l (\$/m³)
 Chemicals cost: k (\$/m³)

Table 2: Detailed Plant Cost for 3000 m³/d

Equipment	Size	No.	Unit cost LE	Total cost LE
Feed tank	3000 m ³	2	408320	816640
Permeate tank	3000 m ³	1	408320	408320
High pressure pump	208.3 m ³ /hr	2	30000	60000
Feed pump	208.3 m ³ /hr	2	15000	30000
Dosing pump		10	800	8000
Sand filter		3	16333.3	48999.9
Mixing station		1	1850	1850
Cartridge housing + cartridges		1	7000	7000
Sand filter packing		3	1333.3	3999.9
Membrane unit		1	150000	150000
PX device		1		23022.15
Total equipment cost				1557832.13



Table 3: Chemicals Cost for 3000 m³/d

Chemicals	kg / Week	Unit Cost \$	Total Cost \$	L/week	
H ₂ SO ₄	1452.25 * 7 =10165.7	\$1.3/kg	13449.25	5524.85	
Sodium hypochlorite 12%	180 * 7 = 1260	\$1.25 /Kg	1575	1135	
Sod. Meta bisulphate 30%	159.5 * 7 = 1116.6	\$3.3/kg	1224.3	1008	
Anti-scalant (Vitec 3000)	14.4 * 7 = 100.8	\$4.14/kg	416.99	80.64	
CIP (Roclean L403)	500Kg/year	\$2/kg	1000		
Sod. Hydroxide	28.8 * 7 =201.6	7.5	1512	140	
Chemicals Storage	Size	No.	Unit Cost \$	Total Cost \$	Material
Acid storage tank	5.3 m^3	1	11200	11200	CS, glass lined
Sod. hypochlorite Tank	0.420 m^3	1	3100	3100	Fiber glass
Sod. Meta bisulphite tank	1.015 m^3	1	6100	4900	st.st. 316
Antiscalant tank	0.085m^3	1	1500	1500	st.st.316
Antiscalant drum	55 gal	1	39	39	Fiber drum
CIP tank	6.25 m^3	1	17300	17300	st.st. 316
CIP drum	40 gal	1	32.8	32.8	Fiber drum
CIP drum	40 gal	1	32.8	32.8	Fiber drum
Sod. hydroxide tank	0.15m^3	1	3000	3000	st.st 316

Table 4: Cost analysis for a plant capacity 3000 m³/d

Equipment cost	Cost
Piping	42367.96
Electrical	6052.57
Building	9078.85
Utilities	30262.8
Site development	3026.28
Ancillary buildings	9078.85
Total	99867.32
PPC	160392.97
Design and engineering	48117.89
Contractor's fee	8019.65
Contingency	16039.3
Total	72176.8
Fixed capital investment (FCI)	232569.78
Total capital investment (TCI)	290712.25
Direct production cost	
Variable	
Raw material	866658
Miscellaneous	23256.98
Utilities	215398.7
Fixed	
Labor	90000
Supervision	18000
Plant overhead	45000
Deprecation	34885.47
Interest	4651.4
Insurance	2325.7
Maintenance	11628.49
Total direct production cost	1,311,804.69 LE

Conclusion

A case study of a reverse osmosis desalination plant with a capacity of 3000 m³/day has been considered to overcome the water shortage in Suez City, Egypt. The design of the plant consists of a proper pretreatment section includes multimedia filtration system as well as cartilage filter, chemical dosing set, antiscalant and feed water disinfection. The membrane unit comprises of 2 stage array, the first array pressure vessels are 20 and the second array vessels are 10, where 6 elements are included in each pressure vessel. The cost investigation of the



RO plant discloses that the major factors affecting the product fresh water cost are the power consumption cost, membrane cost, whereas the chemical treatment signifies almost 10% of the total cost.

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