Designing and optimizing 10,000 m^3/day conventional SWRO desalination plant

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ABSTRACT

Desalination of seawater has been considered as one of the most promising techniques for supplying a fresh water in Libya. Reverse osmosis (RO) is one of the main technologies for big size desalination plants for the reason that it offers an ability of producing a high quality and quantity of fresh water from seawater with a minor specific energy consumption compared to the other thermal evaporation processes. This paper aims to collect and apply the most useful mathematical equations and software of designing a seawater RO desalination plant with a capacity of 10,000 m^3/day. Moreover, its pretreatment equipment such as sedimentation tank, high-pressure pump, multimedia and cartridge filters.

IMSdesign software developed by Nitto Hydranuatics Company used for designing and optimizing the membrane assembly of the suggested plant. Additionally, the energy recovery device (ERD) specification accomplished by the same earlier software. In addition, the recommended antiscalant dose predicted by PWT ProDose software.

The recovery of the plant increased to more than 40% with less number of membrane elements due to installing new advanced membranes (SWC6 MAX) developed by Nitto Hydranuatics Company. Moreover, pressure exchanger device recommended for the designed plant to decrease the specific pumping energy from 4.81 kWh/m^3 to 2.09 kWh/m^3, which saves more energy, thus, decreases the unit product cost of the plant.

Keywords: seawater desalination; reverse osmosis technique, plant design.

1 Introduction

The seawater desalination option is one of the most important strategic decisions for drinking water source in Libya, especially after growing the population and its gathering at the Libyan coast regions, which exceeds 1,900 kms. The option of using RO desalination technology is one of the most recommended technique, because of the efforts of the membrane's manufacturers in developing new membranes with high productivity and quality as well as, the efforts of ERDs manufacturers in reducing the specific energy consumption, by getting benefit of the wasted pressure of concentrated water. Additionally, advantages that make RO desalination as a competitor option compared to the other thermal desalination methods it can be operated and maintained easily with lower operating cost. Furthermore, design flexibility of the plant according to the available space. It should be noticed that the world's largest RO plant was built in Israel at a capacity of 333,000 m^3/d [1].

From the vision of the developments in RO technology and its selection by many countries as a challenging option, this paper aims to design a reverse osmosis desalination plant with a production capacity of 10,000 m^3 / day based on seawater analysis sample of a Libyan coast (Tripoli city), the design includes selecting membrane type, calculation the number of membranes, pressure vessels and several pre-treatment equipment such as sedimentation tank, multi-media and cartridge filters, as well as, high pressure pump and energy recovery device.

2 Proposed Plant Description

The feed water is collected into a sedimentation tank for removing the largest particles and then pumped by transfer pumps through a multimedia filters containing three types of media layers (anthracite, sand and garnet) to reduce the Silt Density Index (SDI) and turbidity to less than 3% and one NTU, respectively. Then a filtered water to be passed through a cartridge filters containing filters with pore size not exceeding 5 microns. The filtered feed water is ready to be pumped through the membrane assembly by means of high-pressure pumps. The desalinated water is then delivered to the product storage tanks and the concentrated water is returned to seawater in some different discharge ways to avoid any environmental problems. Energy recovery devices will be installed in the concentrated stream to reduce the rate of specific energy consumption and thus, reduce the cost of fresh water production. Figure 1 shows the overall schematic diagram of the projected plant.

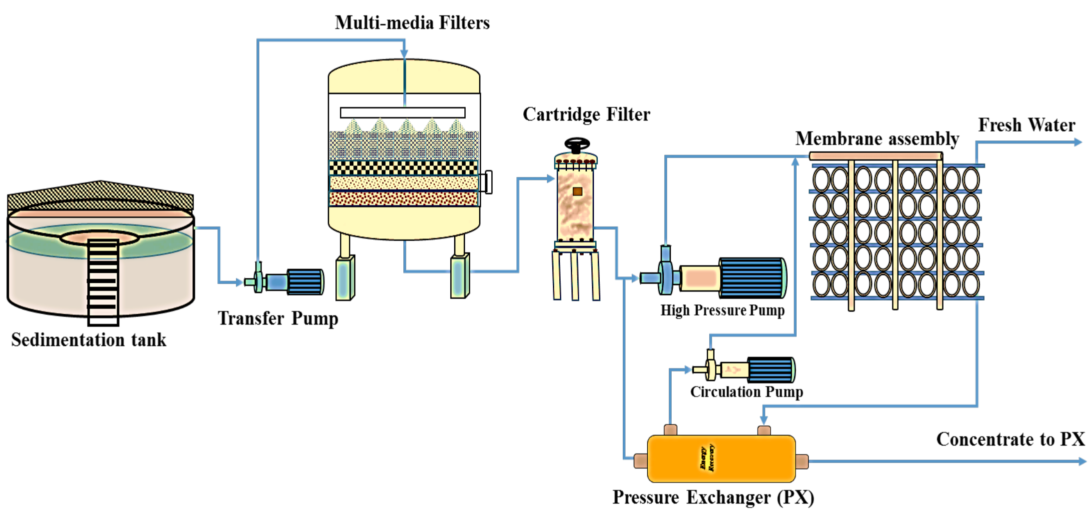

Figure 1: Ggeneral schematic diagram of the proposed plant.

3 Design Calculations

In this section a detailed calculations for all the equipment shown in Figure 1 will be covered in the next subsections, it should be noticed that, the design calculations presented down here are based on seawater analysis of Libyan offshore. The most important required chemical components for plant design are shown on Table 4.

3.1 Clarification (Sedimentation) Tank

The clarification is the first step in feed water pre-treatment section, it is used to give the opportunity for removing the particles that may block the filtration system as well as, to add some chemicals such as disinfectants, coagulants and flocculants if needed.
Sedimentation chamber rise rate and slow mix chamber detention time are the most important factors utilized in sizing clarification tanks.

- Detention Time

Detention time is the theoretical average length of time the water is in the clarifier tank. Detention time depends on two following parameters:

- Volume of the clarifier, and
- Water flow rate.

The detention time can be attained as follows:

$$D_t = \frac{V_c}{F} \tag{1}$$

where

D_t= Detention time

V_c= Volume of clarifier

F= Flow rate

Where the typical detention time of most clarifiers varies between 20 to 30 minutes [2], therefore, the volume of slow mix chamber can be calculated as follows:

$$V_{smc} = F \text{ x } D_t \tag{2}$$

where

V_{smc} = Volume of slow mix chamber

V_{smc} = 535.465 m^3 (Based on 30 minutes detention time).

$$A_{smc} = \frac{\mathrm{V_{smc}}}{\mathrm{h_{smc}}} \tag{3}$$

where

A_{smc} = Slow Mix Chamber Area

h_{smc} = Slow Mix Chamber Height

Where typical height recommended by different companies are between 3 and 6 m.

A_{smc} =146.39 m^2

$$(d_{smc})^2 = \frac{(4)*(A_{smc})}{3.14} \tag{4}$$

where

d_{smc} = Slow Mix Chamber Diameter

$(d_{smc})^2$ =186.48 m^2

d_{smc} =13.66 ~ 14 m

- Rise rate

Rise rate is a main parameter in defining the clarifier efficiency. It is also well-known as the surface loading rate, surface settling rate, or overflow rate. Rise rate is defined as the flow per unit surface area of the clarifier, and it varies between 25 to 75 m^3/d per m^2 [2].

$$A_{TWS} = \frac{F_C}{R_R} \tag{5}$$

where

A_{TWS} = Treated Water Surface Area.

F_C = Clarifier Flow rate

R_R = Rise rate

A_{TWS} = 438 m^2

Therefore, the area of the total clarifier can be calculated as follows:

$$A_{TC} = A_{TWS} + A_{smc} \tag{6}$$

where

A_{TC} = Total Clarifier Area

A_{TC} = 584.41 m^2

$$(d_c)^2 = \frac{(4)*(A_{TC})}{3.14} \tag{7}$$

where

d_c = Clarifier diameter

$(d_c)^2$ = 744.47 m^2

d_c ~ 27 m

3.2 Transfer Pumps

Transfer pumps are used to pump the clarified seawater to the pressure required by multimedia filters, which can be calculated as follows:

Outlet pressure = Required pressure at the top outlet (4.5 bar)

Gross feed flow to filtration plant = 1070.93 m^3/hr

Four pumps are recommended to pump the raw water to filtration system, three in operation and one standby, to avoid plant shutdown during maintenance duties.

Feed flow per pump = 356.97 ~ 360 m^3/hr

Where the pressure and feed flow to filtration plant are known, the transfer pumps can be chosen using a coverage chart, which makes it possible to make a preliminary selection through a group of pump sizes based on a specific impeller speed.

3.3 Multi-Media Filters

The dimensions of the multi-media vessels are calculated as follows:

- Filter Dimensions and Media Quantities
- Diameter

The vessel diameter is based on the normal service flow rate, the service water requirement and the relationship between area and diameter.

$$F_f = \frac{F_{fp}}{N_f} \tag{8}$$

where

F_f = Feed flow per filter

F_{fp} = Feed flow to filtration plant

N_f = Number of filter units

$F_f = 133.87 \frac{m^3}{hr}$

$$A_f = \frac{F_f}{F_{sd}} \tag{9}$$

where

A_f = Required cross sectional filtration area per filter

F_f = Feed flow per filter

F_{sd} = Service down-flow rate

A_f =7.44 m^2

$$ID\ \left(\frac{Af*4}{\pi}\right)^{\frac{1}{2}} \tag{10}$$

where

$ID =$ Required internal diameter

= 3.08 m

- Media Quantities

Table 1 shows the filtering material layers for each media for the designed plant. A typical multi-media filter has the following top to bottom layer configuration (media bed depths shown are the minimum allowed).

- (0.45 - 0.60 m) of anthracite;
- (0.2 – 0.3 m) of sand, and
- (0.10 – 0.15 m) of garnet [3].

Table 1: *Filtering material*

Filtering material layer	Grain size, mm	Layer depth, m (in)	Media quantity (m^3)
Anthracite	0.85–0.95	0.6 (23.6)	4.5
Sand	0.45–0.55	0.3 (11.8)	2.2
Supporting layer (Garnet)	0.3	0.15 (5.9)	1.1

$$Q_M = L_T * \frac{(ID)^2 * \pi}{4} \tag{11}$$

where

$Q_M =$ Media Quantity

$L_T =$ Layer Thickness

Straight Shell Height

A multi-media filter requires 50% minimum freeboard to allow bed expansion during the backwash cycle.

$\text{Straight}_{\text{Shell Height}} = (\text{Depth}_{\text{Anthracite}} + \text{Depth}_{\text{Sand}} + \text{Depth}_{\text{Garnet}}) \text{ x } (1 + 50\% \text{ Freeboard})$

$\text{Straight}_{\text{Shell Height}} = 1.58$ m

- Service and Backwash Performance per Filter
- Service Flow Rate

The allowable flow rate through a multi-media filter is 290 - 530 $m^3.d^{-1}/m^2$. Normal service flow is 290 - 350 $m^3.d^{-1}/m^2$. Flow rates of 470 - 530 $m^3.d^{-1}/m^2$ should only be used for short periods of time, when one filter is being cleaned and the other filters must temporarily process the higher flow rate. Flow rates above 530 m^3.d-1/m^2 must not be used, as impurities will be driven through the media bed.

Gross water throughput per filter unit per cycle = Feed flow per filter $*$ Backwash frequency (13)

Gross water throughput per filter unit per cycle= 3212.79 m^3

- Backwash Flow Rate

The backwash flow rate is an essential parameter to expand the filter media depth via 30%, it depends on temperature, because the pressure pushing up the filter media is a function of the water viscosity, which decreases with increasing temperature.

Backwash flow rate (without air)=Required cross-sectional filtration area per filter x Water up flow during backwash (without air) (14)

Backwash water flow rate (without air) = 260.4 $\frac{m^3}{hr}$

Backwash time (without air) = 10 min

Backwash water volume (without air)= $\frac{\text{Backwash water flow (without air) x Backwash time without air}}{60}$ (15)

Backwash water volume (without air)= 43.38 m^3

Raw water volume used to rinse= $\frac{\text{Feed flow per filter x Rinse time (at service flow)}}{60}$ (16)

Rinse time (at service flow) = 5 min

Raw water volume used to rinse = 11.16 m^3

Water up-flow during backwash - together with air = Air up-flow during backwash + Water up-flow during backwash - without air (17)

Water up-flow during backwash - together with air = 85 m/h

Backwash water flow rate (with air) = required cross sectional filtration area per filter $*$ Water up-flow during backwash - together with air (18)

Backwash water flow rate (with air) = 632.4 m^3/hr

Backwash water volume (with air) = $\frac{\text{Backwash water flow (with air)} * \text{Backwash time with air}}{\text{60 min}}$ (19)

Backwash time with air = 5 min

Backwash water volume (with air) = 52.68 m^3

Total filtered water volume required for backwash = Backwash water volume (without air) + Backwash water volume (with air) (20)

Total filtered water volume required for backwash = 96.06 m^3

Total filtered and raw water required for backwash = Raw water volume used to rinse + Total filtered water volume required for backwash (21)

Total filtered and raw water required for backwash = 107.22 m^3

- Rinse Flow Rate

To adequately rinse the media bed, the flow rate must be at least 350 $m^3.d^{-1}/m^2$ for 1 bed volume.

Rinse Flow = Rinse Flow Rate $*$ (Diameter) ^{2} $* \pi/4$ (22)

Rinse Flow = 2607.71 m^3/d

- Air Scour Flow

For an effective air scour, the air flow rate of the recommended design blower must be at least 50 m^3.hr -1/m^2 (3 SCFM/ft^2) at 0.5 bar.

Air flow-rate requirement = Required cross-sectional filtration area per filter $*$Air up-flow during backwash (23)

Air flow-rate requirement = 371.85 m^3/hr

- Net Production per Filter

Net production of filtered water = Gross water throughput per filter unit per cycle- Total filtered water volume required for backwash (24)

Net production of filtered water = 3116.73 m^3

Time of production of net volume filtered water = Backwash frequency-(Backwash time with air + Backwash time without air+ Rinse time (at service flow))/60 (25)

Time of production of net volume filtered water = 23.67 hr

Net production rate of filtered water = Net production of filtered water/ Time of production of net volume filtered water (26)

Net production rate of filtered water =131.69 m^3/hr

Net production rate = Net production rate of filtered water $*$ Number of filter units (27)

Net production rate = 1053.54 m^3/hr

3.4 Cartridge Filters

The filter elements of a cartridge filter are selected based on two measures, the nominal micron rating and the service water flow rate. The standard diameter of the filter elements is 2.5 inches. The standard length of the filter elements can be either 30 or 40 inches. The choice of 30-inch or 40-inch cartridges often depends on the availability of standard filter housings. In general, there is not much cost difference between housings for 30-inch or 40-inch cartridges, so if there are no other constraints a 40-inch cartridge system generally is the most economical.

- Filter Element Quantity and Height

The number of 10” lengths of cartridge required for a system can be calculated as follows:

Quantity = Service water requirement / Flow per 10-inch length (28)

(10-inch lengths) (at available pressure drop)= 1170.6 ~1171 element

Using a filter element that can support 0.9 m^3/h per psid per 10-inch length, the quantity of filter elements for the entire system can be calculated as follows:

$$\text{Quantity (40-inch lengths)} = \frac{\text{Quantity (10−inch lengths)}}{\text{Quantity (10−inch elements per element)}} \quad (29)$$

= 292.75 ~ 293 element

No. of cartridge vessels = Quantity (40-inch lengths) / Quantity per vessel (30)

= 5.86 ~ 6 cartridge vessels

Feed flow per filter = Service water requirement / No. of cartridge vessels (31)

Feed flow per filter = 175.59 $\frac{m^3}{hr}$

3.5 High Pressure Feed Pump

Selection of the high pressure pump (HPP) depends on the minimum and maximum flow rates, discharge pressure required, suction pressure available and the maximum temperature, where these parameters can be obtained from IMSDesign detailed report. Table 2 shows design parameters of the high pressure feed pumps.

- Variable Speed Pumps

Variable speed motors are used to control motor operating speed. This allows a pump to operate at different speeds and thus reduce pump size and/or number of stages and eliminate the need for a speed-increasing gearbox in some applications. High-speed pumps are especially useful for high head, low-flow applications and the ability to alter pump speed allows operation over a wide range of conditions. Variable speed drives also provide a pump system with a built-in soft start and stop to prevent shocks to the system and water hammering to the membranes.

Table 2: *High pressure pump design parameters*

Power Calculation (without ERD)	
Pump pressure (bar)	52.9
Product flow m^3/d	10000
Pump flow m^3/d	25000
Pump efficiency %	83
Motor efficiency %	93
VFD efficiency %	97
Power/stage/pass Kw	2004.4
Brake horse power BHP	2686.8
Total pumping power kW	2004.4
Pumping specific energy kwh/m^3	4.81

3.6 Reverse Osmosis Membrane System

The following steps were used to design the membrane assembly of the SWRO desalination plant.

- Selection of Membrane Element Type

Elements are selected according to feed water salinity, feed water fouling tendency, required productivity and salt rejection, as well as energy requirements, where the membrane selected for the designed plant is SWC6 and IMSDesign software were used to give the information required for the designed system. This software is available on the Website of Hydranautics Company. Table 3 lists all the specifications of SWC6 MAX membranes.

Table 3: *Membrane specifications (*SWC6 MAX)

Performance	
Permeate Flow	50 m^3/d
Salt Rejection	99.8% (99.7% min)
Applied Pressure	55 bar
Type	
Configuration	Spiral Wound
Membrane Polymer	Composite Polyamide
Membrane Active Area	40.8 m^2
Application Data	
Maximum Applied Pressure	83 bar
Maximum Chlorine Concentration	< 0.1 ppm
Maximum Operating Temperature	45 ^oC
pH Range, Continuous (Cleaning)	2-11
Maximum Feed water Turbidity	1.0 NTU
Maximum Feed water SDI (15 mints)	5
Maximum Feed Flow	17.0 m^3/h
Minimum Ratio of Concentrate to Permeate Flow for any Element	5:1
Maximum Pressure Drop for Each Element	15 psi

- Selection of Average Membrane Flux

The flux design selection depends on an experimental data, experience where the typical membrane design fluxes based on the feed supply. The recommended design flux for this plant is 13.5 l/m²-h.

- Number of Elements Needed

The number of elements N_E can be calculated using equation (32) by dividing the design permeate flow rate Q_P by the design flux f and by the membrane active area of the chosen element S_E (ft^2 or m^2).

$$N_E = \frac{Q_P}{f.S_E} \quad (32)$$

where

N_E = Total number of elements.

Q_P =required permeate flow.

S_E = Membrane active area, and

f = Average flux.

N_E = 756 membrane elements

- Number of Pressure Vessels Needed

For this plant, 6-element vessels will be used, so, the number of pressure vessels will be:

$$N_V = \frac{N_E}{N_{EpV}} \quad (33)$$

where

N_V = Total number of pressure vessels.

N_E = Total number of elements; and

N_{EpV} = No. membrane element per PV.

N_{EpV} = 756 / 6 = 126 PVs

- Number of stages selection

The stage number of the RO planta describes the number of pressure vessels in series, where the inlet feed water will goes through till it leaves the desalination plant as brine. Typically, the number of serial element positions is linked with the system recovery and the number of stages, for the designed SWRO plant the recovery is 40% and one stage plant will be selected to avoid the expected scaling problems and the uncaring in operation and monitoring of the plant. The RO stage consist of two parallel RO racks with 126 pressure vessels. Each pressure vessel contains six spiral wound RO membranes.

Table 4: *Seawater analysis (Libyan offshore sample)*

PH	8	CO_3	12.653	mg/l
Cations	mg/l		Anions	mg/l
Ca	455		HCO_3	163
Mg	1427		SO_4	2915
Na	11600		Cl	20987
K	419		F	0
NH_4	0		NO_3	0
Ba	0		PO_4	0
Sr	0		SiO_2	2
Cal. TDS	37981		B	0

- Membrane Systems Report

Integrated Membrane Solutions Design (IMSDesign) software was used to design, optimize and analyze the performance of the designed plant and testing the configuration according to seawater analysis shown in Table 4. The design parameters of the designed desalination plant are presented in Table 5.

Table 5: *Design parameters of the plant*

Company Name	Hydranautics
Design software used	IMS design
Pressure vessels (PVs) configuration	1 stage
Permeate recovery %	40
Average flux, lmh	13.5
No. of pressure vessels (PVs)	126
No. of membranes	756
No. of membranes per (PV)	6
Nominal diameter, inch	8
Membrane model	SWC6 MAX
Max. operating pressure, bar	83
Working pressure, bar	52.9
Ph	8
Maximum temperature, ^{o}C	45
Feed flow, m^3/d	25000
Permeate flow, m^3/d	10000
Concentrate flow, m^3/d	15000
Design salt rejection, %	99.6
Concentrate salinity, mg/l	63119.2
Permeate salinity, mg/l	295.51
Feed salinity, mg/l	37981

3.7 Energy Recovery Devices (ERD)

In SWRO desalination plants, about 55 to 60% of the feed pressure leaves the plant with approximately 870 psi (60 bar) through the brine stream. This energy can be recovered to decrease the specific energy consumption of the plant using turbocharger, pelton wheel and pressure exchanger.

Table 6: *Pressure exchanger parameters*

Parameter	Power Calculation (without PX)	Power Calculation (with PX)	
	Pass 1	Pass 1	ERD boost
Pump pressure (bar)	52.9	54.1	1.7
Product flow m^3/d	10000	10000	-
Pump flow m^3/d	25000	10153.9	14846.1
Pump efficiency %	83	83	83
Motor efficiency %	93	93	93
VFD efficiency %	97	97	97
Power/stage/pass Kw	2004.4	832.6	37.2
Brake horse power BHP	2668.8	1116	49.9
Total pumping power kW	2004.4	869.8	
Pumping specific energy kwh/m^3	4.81	2.09	

The high-pressure concentrate is fed into the energy recovery device, where a pressure exchanger (PX) will be suggested for this plant. This PX supplies about 94 % of the high-pressure pump's energy requirement. Table 6 shows power calculation of the designed plant with and without pressure exchanger, which is achieved by IMSDesign software.

3.8 Chemical Requirements

Most of SWRO desalination plants need some chemicals to be added to the feed water before passing through the membrane assembly. The chemicals are dosed based on the feed water analysis, there are several chemicals added to the feed water such as disinfectant, coagulant and flocculants, sodium meta-bisulfide if chlorine is injected to the feed water. In this design the feed water needs to be treated with antiscalant to prevent the scales accumulation on the membranes surface. A detailed information will be described in the following subsection.

- Antiscalant

For dosage rate calculation of antiscalants, the manufacturers should be contacted. Overdosing should be avoided. Attention must be taken that no significant amounts of cationic polymers are existing once dosing an anionic scale inhibitor, because precipitation reactions may happen, similarly may occur, by dosing a negatively charged antiscalant and cationic polyelectrolytes or multivalent cations (e.g., aluminum or iron). In SWRO plants working with total dissolved solids of more than 35,000 mg/L, scaling is not that problematic as in brackish water desalination plants BWRO since the permeate recovery of the SWRO plants is limited to 30-45%, but still, an antiscalant is recommended if operating the SWRO plants with a permeate recovery of 35% or more [4].

A computer model developed by Professional Water Technologies, Inc. was used to determine the performance of an antiscalant (TITAN ASD 200 SC LIQUID SUPER CONC) supplied by the same antiscalant manufacturer. Table 7 shows the results of the computer model indicate that an antiscalant dose of 0.2 mg/l at the feed side and 0.3 mg/l at the concentrate side would effectively control membrane scaling based on the input feed water chemistry and a design recovery of 40 percent.

Table 7: The suggested antisclant dosage rate

Product Selection	
TITAN ASD 200 SC LIQUID SUPER CONC	
Recommended Dose Rates	
Feed (mg/l)	Concentrate (mg/l)
0.2	0.3
Est. Product usage (100%)	
kgs/day	mt/yr

4 Results and Discussion

The plant designed with advanced SWC6 MAX membranes increases the productivity of the plant with less number of membrane elements and pressure vessels, this design was compared with an existing SWRO plant in Tajoura, with the same capacity, it is found that the number of elements, as well as the number of pressure vessels were decreased from 1080 element to 756, which will decrease the cost of the next membrane replacement as well [5]. Furthermore, the pumping specific energy of the HPPs were decreased due to installation of PX with a hydraulic efficiency in the range of 94-96%, in addition to that the overall recovery were increased from 35% to 40% and it can be increased to more than 50%, but the researchers suggested 40% recovery to avoid scaling, fouling problems and decreasing chemicals consumptions. As far as the pressure exchanger was selected as ERD for designed SWRO plant, the pressure exchanger conversion efficiency of more than 94%, and therefore, the unit designed saves more than 60 % of the destroyed power, which will decrease the unit product cost.

5 Conclusion

In conclusion, the SWRO desalination plant were designed and optimized using IMSDesign software. Furthermore, some mathematical equations were collected and applied for designing several pretreatment equipment. Therefore, the design was prepared and ready for development by other researchers or students; whatever other ideas of SWRO plant design are becomes recognizable.

The optimal design of SWRO process has been addressed in this work using an advanced membrane (SWC6 MAX) developed by Hydranautics Company. The design of plant with a new SWRO element had improved permeability and quality; these features provide system designers with new options to reduce the capital cost of the system as well as, the operating cost. Although the new low energy membranes run at lower pressure.

The greatest sensible and applied way to rise efficiency or decrease the power input of the designed plant meaningfully seems to be replacing the throttling valve and old turbine or reverse running pumps on the brine stream by modern pressure exchanger, the use of a pressure exchanger as energy recovery system enables decreasing the total pumping power of the reverse osmosis desalination plants.

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