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Engineering design of Qingdao seawater desalination plant

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ABSTRACT

With a production capacity of 100,000 m^3/d, Qingdao seawater desalination plant (SWDP) will be located in the eastern part of China (Shandong Province) and it is being developed under a 25-year DBOO contract in order to supply drinking water to this city. The Qingdao SWDP is situated near to a seawater lagoon shared with other already existing factory and the raw water is withdrawn to it from the shallow waters of the bay by means of a submerged pipe when the tide is high. Therefore, the raw water has a high suspended solids values and a high level of pollutants. The desalination technology selected has been reverse osmosis (RO) with a previous and specific pre-treatment which has been designed to get optimal seawater previously to RO membranes. This pre-treatment consists on: self-cleaning travelling screen, dissolved air flotation (DAF), 100 μm filtration, ultrafiltration (UF). Nowadays, to determine the feasibility and efficiency of the process, it is performing some experimental tests by means of different pilot studies. Therefore, this paper shows the engineering design of a high efficiency SWDP that will significantly increase the water resources of the region.

Keywords: Desalination; Reverse osmosis; Seawater; Design; Engineering

1. Introduction

Qingdao seawater desalination plant (SWDP) is located in the eastern part of China (Shandong Province) and it is being developed under a 25-year DBOO contract between the Municipality of Qingdao and Befesa Agua in order to supply drinking water to this city with a production capacity of 100,000 m^3/d.

It is situated near to a seawater lagoon (Fig. 1) shared with other already existing factory (Soda) and the raw water is withdrawn to it from the mentioned lagoon that receives its inflows from the shallow waters of the bay by means of a submerged pipe when the tide is high.

Works on the lagoon property of Soda will also be necessary and these include the enlargement of the lagoon and the inclusion of two pumping stations, one for increasing the capacity of the lagoon to withdraw water from the bay at high tides and the other for pumping the water to SWDP more than 1 km away from it.

2. Key issues of the design

This plant owns several singular characteristics that have influenced the design. The first of them is the lagoon from which seawater to the process will be

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Fig. 1. Views of the lagoon, pilot plant and algae.

pumped. It is located at a short distance from the shore of Jiaozhou Bay. Actual average lagoon depth is 5 m with an area of 40,200 m^2. It is not enough for satisfy Soda and SWDP future demands (26,612 m^3/h), therefore, part of the works will include enlargement of it up to reach more that 400,000 m^3 by dredging the bottom up to a depth more than 8 m. At the same time, because the existing pipes that communicates the lagoon with the bay are not sufficient to drain the required water by gravity at high tide, a pumping station with three pumps (two in operation, one stand-by) of 350 kW and 10 m.w.c. each will have to be installed to withdraw the additional 12,000 m^3/day that would not be achieved otherwise by gravity. Retention time in the lagoon will overpass 12 h while theoretical studies on sedimentation required time show that particles above 50 μm should settle in about 8 h. That will require on the other hand daily dredging of the lagoon to keep it clean of mud.

Other remarkable issue that has also influenced the design and that is linked to the lagoon is the fact that Soda will be paid for the withdrawn waters as a compensation for the investment that they will have to undertake, the operation of the lagoon filling and its maintenance. Because of this and also influenced by the poor quality of the water so that not very high ultrafiltration (UF) recoveries were expected, first design of the plant considered minimisation of the intake flow and recirculation of UF backwash waters to the inlet of the plant. However, after several months of pilot studies and the convincement of the design team that UF recoveries above 85% would be safely achieved, the design turned to a non-recycling backwash waters design since the economical assessment made did not justify it and the operation would become more complicated.

Weather conditions and the particularity of the shallow waters of the lagoon also influence the reverse osmosis (RO) design. Due to the size of the lagoon, its waters suffer a significant variation in temperature throughout the year (1–24°C). Logically, the flow of water coming into the plant also fluctuates and therefore the conversion rate. Otherwise, the fluctuation in pressures would have become too wide to operate the main equipment around their best efficiency point (BEP). Summarizing, the design will try to keep RO required pressure as constant as possible varying other parameters such as the flow entering the plant and hence, the conversion rate, getting a constant amount of water to the product throughout the year.

It is also worth saying that the design opted for a conservative design on the pre-treatment based on for a first stage dissolved air flotation (DAF) and a 2nd stage pressurized UF because of the expected poor incoming water qualities. In case seasonal variations allow it, the DAF unit might well be by-passed.

Other interesting conclusion draw from the pilot tests is the fact that the option for submerged UF is not preferred since TMP required along the year would easily overpass 80 MPa, close to the acceptable limit.

Several types of UF pressurized membranes have also been tested and all of them showed a good performance, acceptable backwashes frequencies, good capability of recovery after CEB and CIP's and good recoveries regardless the type of material or whether the flow was outside-in or inside-out. Because of the size of the plant, a high number of UF trains will in any case be necessary allowing very low fluctuations in flows and pressures when one unit is taken out or reincorporated for backwash. This has been benefited by providing and in-line UF design with RO, that is, no intermediate buffer tank exist between UF process and RO and therefore power consumption and capital costs are reduced.

Finally, it is also interesting to draw the attention to the need of an intermittent partial 2nd RO pass to fulfil boron product requirements depending on water temperature and membrane fouling.

3. Sea water characteristics

The design has been based on next attached seawater analysis as it can be observed in Table 1.

Table 1
Physicochemical parameters of the raw water.

Turbidity	7	NTU	pH	7.70	Units
Colour	>5	Units	TDS	36,247.2	mg/L
Temperature	3–28	°C	Total alkalinity	115	mg/L
Oil and grease	<0.1	mg/L	Total oxygen dissolved	5.57	mg/L
TOC	14	mg/L	TSS (1–5 μm)	12	mg/L
Total coliform	79	MPN/100 mL	TSS (5–25 μm)	14	mg/L
Total hardness	5.41×10^3	Mg/L $CaCO_3$	TSS (25–50 μm)	20	mg/L
			TSS (>50 μm)	20	mg/L

To provide an idea of the biological fouling potential of this water it must be said that after a preliminary identification, 44 species of phytoplankton samples were determined (all belong to Phylum Bacillariophyta and dinoflagellate type like *Skeletonema costatum* (*Greville*) *Cleve, Odontella regia* (*Schultze*) *Simonsen*, etc.).

Other interesting and positive fact that must be mentioned is that despite the algae tide that took place this summer and that was well-known worldwide because it was just prior to the Sailing Olympic Games that were held in the City of Qingdao, the lagoon water quality remained steady and since then not even TOC unusual increases have been detected (Fig. 1).

4. Product water requirements

After the process of desalination, water product must be suitable for human consumption according to the 'National Standard of People's Republic of China. Standard for drinking water quality (GB 5749-2006) on the next limiting values of the water quality:

- Turbidity: 1 NTU (it is 3 if under restriction of water source and treatment techniques).
- pH: 6.5–8.5
- Chlorides (mg/L): <250
- Sulphates (mg/L): <250
- TDS (mg/L): <1000
- Total hardness (based on $CaCO_3$) <450 mg/L
- Additionally, boron values should be bellow 0.5 ppm

5. Process description

Befesa's Qingdao SWDP includes the water intake pumping station and the piping to the plant, its pre-treatment and the generated sludge treatment, the RO stage and the brine discharge. Next, it will be explained briefly each process. A diagram can be observed in the Fig. 2.

5.1. Pre-filtering and pumping of seawater

Seawater, once it is captured directly from the existing raw water intake, will enter a pumping station exclusively dedicated to pump it to the SWDP. The idea of sharing the pumping station with Soda was rejected because of the inappropriate use of the materials in other existing pumping station. This intake pumping station has been designed with two inlet channel with a bar rack and a self-cleaning travelling screen to remove the bigger solids, before feeding a common wet well. Flow necessary for the production of the SWDP is 12,000 m^3/h (maximum flow), therefore, two plus one on reserve pumps, 6000 m^3/h each one and T.D.H. 15 m.c.w., equipped with frequency drivers have been chosen to pump the raw water to SWDP pre-treatment stage.

5.2. Chemical reagents

To get desired quality water, it is necessary to add some chemical reagents.

- Sodium hypochlorite: Chlorination on discontinuous basis will be achieved by dosing this reagent in the water intake wet well. The concentration is at 12% with a designed dosing of up to 8 ppm.
- *$FeCl_3$*: Again, dosed in raw water intake to eliminate suspended and colloidal matters from the seawater as a coagulant. It will be dosed once diluted at 20% up to 10 ppm in the main stream.
- *Sulphuric acid*: It will dose in raw water intake at 96% concentration to reduce the pH of the seawater in order to prevent precipitation of calcium carbonate and to enhance coagulation process with a maximum dose of 35 ppm.
- *Polyelectrolyte*: The polyelectrolyte solution (flocculant) will be prepared in two dilution system and injected before DAF system, if it is required (max. 1 ppm).
- *Sodium bisulphite*: Before first pass RO system to eliminate residual chlorine and decrease the redox potential of the sweater with a maximum dose of 6 ppm.

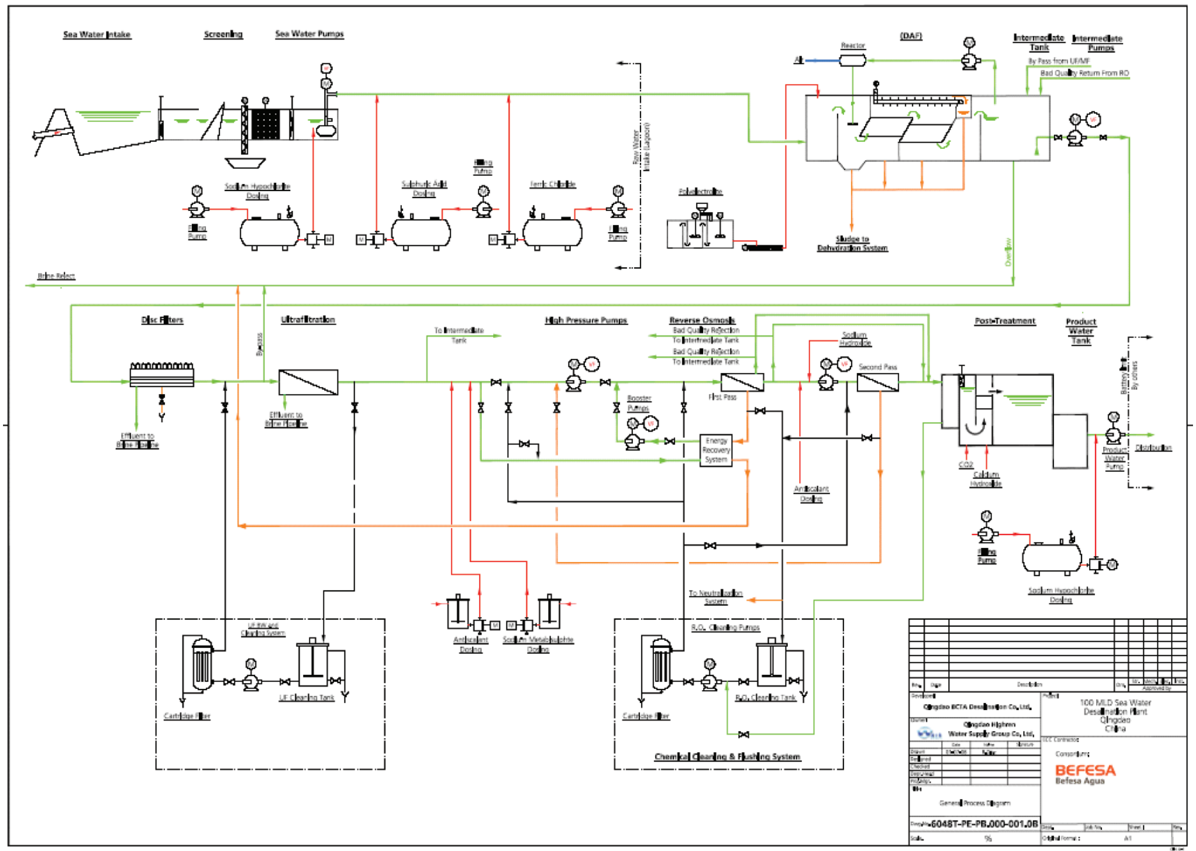

Fig. 2. Process diagram of the Qingdao SWDP.

- *Antiscalant*: This reagent will be dosed before both 1st and 2nd pass RO system to prevent the precipitation of certain salts (max. 2 ppm).
- *Sodium hydroxide*: It will be dosed before 2nd pass RO system because it could be necessary to eliminate boron (max. 10 ppm).

5.3. Dissolved air flotation (DAF)

As it is well known, DAF systems are based on the principle of the solubility of the air in water under a certain pressure and the release of it at atmospheric pressure to generate sufficient amount micro-bubbles of air (80–100 μm) to elevate the flocs to the surface where they are continuous or periodically retired by mechanical means. In the case of Qingdao SWDP, six DAF lines have been design, with a capacity of 2000 m^3/h per line (2240 m^3/h included recirculation flow), total capacity 12,000 m^3/h. Under normal flow conditions the DAF system load will be 35 m^3/m^2/h (reaching up to 35 with highest flows), however, lamella stacks inside the DAF's units ensures that final Hazen velocity will be not higher than 7.5 m^3/m^2/h. For the pressurization system, each DAF unit operates with its own pressurization vessel of 1.5 m^3 in capacity operating under 6 bar of pressure. Between 10% and 15% of the flow will be recycled for pressurization with air. A/S ratio is conservative with a value of 0.3; This can however be explained for this type of DAF applications since TSS are no as high as in wastewater applications.

5.4. Intermediate pump station

After DAF system, seawater will enter to an intermediate basin and will be pumped in line up to the high-pressure system after previously passing through an automatically backwashed strainer system (MF/UF suppliers requirement as protection system) and the MF/UF system. Pumps will be centrifugal and horizontal type in a 2 + 1R pumps configuration, each of them of 6000 m^3/h and 58 mcw capacity and they discharge in a GRP 1300 mm pipe.

5.5. Strainer system

In order to protect MF/UF system (remaining suspended solids will be eliminated), seawater passes through an automatically backwashed strainer system with 200 μm mesh size. Inlet and outlet pipes and collectors are made of GRP and their diameter is such that the passage speed never exceeds 2.5 m/s.

5.6. MF/UF system

At the beginning there were two possible configurations considered in this part of the process: pressurized and submerged. However, based on pilot tests studies performed up to date (Fig. 1), it appears that pressurized option is the most suitable due to the high TSS content that might enter to the MF/UF that might force to operate a submerge system very closed to its maximum allowable TMP. Pressurized MF/UF tests, in turn, have shown very stable on TMP behaviour at normal recommended fluxes for each type of tested membranes and without very high-demanding backwashes (BW) frequencies. It is however still open the final pressurized system configuration depending on selected membrane supplier in the market. Pressurized PVDF and PES membranes running on outside-in flows and opposite have been tested and all of them have behaved well during tests. Preliminary and very general conclusion on this tests lead us to find advantages on the less water amount required for backwashing found on those that are aided with air during backwash, hence higher recovery rates can be achieved, and this is important in this particular project since the plant must pay a fee for the seawater used. Other conclusion is that those with better hydrophilic characteristics require lower TMP pressures with even much higher fluxes. In any case, recoveries above 85% in the MF/UF units have proved to be achievable with both systems allowing BW frequencies above 30 min with chemical enhanced backwashes (CEB) above 12 h. TMP will range depending on the system between 0.4 and 1 bar.

5.7. RO system: first and second pass

SWDP is design under the concept of five independent RO lines, each of 20,000 m^3/day capacity. These lines, because of the variable recovery rate design depending of operation conditions must be equipped with frequency drivers to provide the required flexibility in pressure and flows. High-pressure pump group includes high-pressure pumps, pressure exchanger as energy recovery system and booster pumps:

High-pressure pumps: In RO first pass, there will be same number of motor-pump groups as lines (5) with a flow of 925 m^3/h and T.D.H. (maximum): 700 mcw with high Voltage VFD equipped. One complete non-installed group will also be kept in reserve. Feed pipes of the pumps are made of GRP. The discharge/outlet pipes of the pumps (high-pressure pipes) are made of seawater-resistant materials (stainless steel). The brine is transferred to all the pressure exchangers.

– *Energy recovery system*: Brine energy is recovered at the outlet of the membranes by means of hyperbaric/compression chambers.
– *Booster pumps*: Pumps per rack: 1 unit; total number of pumps: 5 + 1R (non-installed); flow per pump: 1250 m^3/h; T.D.H. (maximum): 51 mcw; low voltage VFD equipped
– *RO second pass pumps*: Pumps per rack: 1 unit; total number of pumps: 2 + 1R (non-installed); flow per pump: 1250 m^3/h; T.D.H. (maximum): 200 mcw; low voltage VFD equipped

To carry out the desalination process, spiral wound membranes will be used with pressure vessels with seven membranes everyone. The proposed design consists on a first pass with five trains and a second pass of double stage with two trains. Membrane system recovery is established between 40% and 46% being for the first and second pass is from 40% to 46% and 90% respectively.

5.8. Product water

The product water will be stored in two separate tanks with a capacity of 10,000 m^3 each one. It will include low and very low level switches for the alarms and for triggering the product water pumps. It will have man holes for inspection and maintenance purposes.

The product water post-treatment consist on re-adjust the pH due to the rejection of large ions by RO membranes, RO permeate have low pH and very little calcium and bicarbonate. As a result, RO permeate are always very corrosive. In order to obtain the acceptable pH and LSI values, CO_2 and lime dosing will be dosed before entering the product water tank. Later, a disinfection stage with sodium hypoclorite is carried out up to archive a residual concentration of chlorine of 0.5 ppm.

Finally, once the product water has been post-treated, it will be pumped by means of 2 + 1R pumps, selected for 2100 m^3/h each one and 70 mcw (preliminary design).

5.9. Brine discharge

With a diameter of 1600 mm and 1260 m long, brine reject pipeline will be used to transport brine from RO system to the sea.

5.10. Dehydration system

Sludges produced in pre-treatment DAF system will be treated in a dehydration system.

6. Conclusions

Qingdao SWDP design can be defined as a very challenging plant because of the quality and temperature variations of the seawater this has lead to a flexible design based on variable recovery rate to overcome the huge pressure gap that would have to be covered otherwise, therefore allowing all devices to operate in a reasonable BEP in all their operational range.

Beside that and because of the particularity of the fee to be assumed by the SWDP on the seawater withdrawn from the lagoon, several pre-treatment configurations have been analyzed and at the same time that assumptions have been supported by pilot tests. At the light of this analysis and test results, normal MF/UF recovery rates are expected and therefore it seems that there is no need for recycling backwashing waters to the process. It appears clear also, that pressurized MF/UF systems are preferred based on a more conservative design that will make them work in a safe zone far from their operational limits. Pilot test, up to date, have not ended and not a final decision has been taken yet on the MF/UF final configuration.