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Optimization of the reverse osmosis seawater demineralization technologies for a power producing industry

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ABSTRACT

In the present work an optimization analysis of the main operating costs of the Black Sea water demineralization processes has been carried out. Several conventional and unconventional technologies utilizing membrane and ion exchange methods were considered. It is demonstrated that a double-stage reverse osmosis employing medium and low density membranes can be successfully used instead of conventional high pressure reverse osmosis for the demineralization of the Black Sea water. This allows decreasing main operating costs by 15–28%. Potable water can be obtained in membrane process without final remineralization by applying double-stage process based on nanofiltration and low density membrane elements. Main operating costs are by 15–35% lower compared with conventional seawater treatment processes.

Keywords: Seawater desalination; Membrane technology; Costs optimization

1. Introduction

Thermal and nuclear power plants are considered as large industrial water consumers. The requirement to use deeply demineralized water in technological processes of these enterprises is conditioned by high heat loads on the equipment which uses water as working medium (steam raising) or heat carrier (cooling circuits). Technological losses in circulating cycles of thermal plants and nuclear power stations are compensated by makeup water, previously treated on CWP station with a typical capacity 150–300 m^3/h [1].

The need to solve energy problems of regions in coastal areas resulted in the emerging of energy generating facilities, which use seawater containing 10–45 g/dm^3 of TDS as feed. As a rule, demineralization technologies in these cases are double-stage reverse osmosis or combined technology comprising reverse osmosis and ion exchange (H-cycle on strong acid cation exchanger and OH-cycle on strong base anion exchanger) [2]. Strict requirements to demineralized water quality can be satisfied by inclusion of a final treatment stage — MB or electrodeionization.

General scheme of a multistage seawater conditioning process for power producing industry is presented in Fig. 1.

In the context of optimization analysis aimed to economic and ecological parameters the water demineralization stage is of the highest interest, since the main part of operating costs and energy consumption is provided here. Wastes formed on this stage determine the ecology of the process as a whole.

Reverse osmosis technologies based on the application of SW membranes and high-pressure pumps with energy recovery devices are widely used for seawater desalination [3]. They provide the possibility to decrease seawater mineralization with initial TDS ~40 g/dm^3 to

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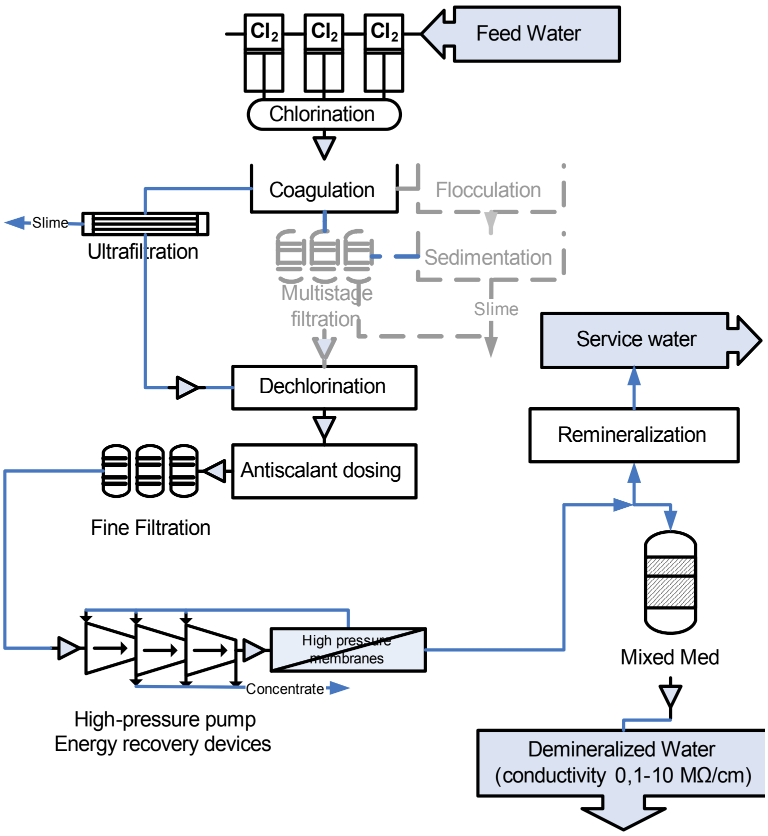

Fig. 1. General scheme of the seawater conditioning process for a power producing industry.

~100–500 mg/dm^3 in a one stage. In the economic context the weakest points of the technology are high power consumptions caused by high-pressure pumps and significant capital and operation costs caused by high price of SW elements [4].

In the context of ecology membrane group of methods can be characterized as comparatively safe as it requires the use of minimum amount of chemical reagents. However all membrane processes result in formation of concentrates containing mineral components. TDS of the concentrates can exceed natural seawater mineralization more than 2–3 times. Discharge of such concentrates negatively affects sea flora and fauna. According to a number of studies, WW TDS can be considered as acceptable if it does not exceed the mineralization of natural seawater more than 1.5–2 times [5].

Progress in fields of membrane synthesis and application significantly extended the possibilities of membrane processes. It became possible to consider membranes of different densities — high (SW), medium (BW) and low (TW, LE and NF) for non-conventional applications. For example economic expediency of nanofiltration and reverse osmosis membranes instead of SW membranes for desalination of the Caspian Sea water (TDS ~10 g/dm^3) was shown in the study [6].

2. Objective of the study

In the frame of the present work an optimization analysis of main operating costs of the Black Sea water demineralization processes will be done. Several conventional and unconventional technologies are of prior interest: one-stage reverse osmosis utilizing high density membranes, double-stage reverse osmosis utilizing middle and low density membranes and combined schemes comprising reverse osmosis and ion exchange stages.

3. Objects and methods

The Black Sea water was considered as raw water for all technological calculations. Typical composition is shown in Table 1.

MOC of reverse osmosis technologies include:

- Expenditures for membrane elements taking into account their service life in control conditions (according to the technical specifications);
- Specific energy costs.

MOC of ion exchange technologies include:

- Expenditures for ion exchange resins taking into account additional annual expenses (10% from the total extent);

Table 1
Composition of the Black Sea water

Component	Content, mg/dm^3
Ca^{2+}	146
Mg^{2+}	548
$Na^+ + K^+$	4530
HCO_3^-	81
SO_4^{2-}	1305
Cl^-	8626
TDS	15000

- Expenditures for regenerating agents (acids and alkali).

The estimation of ecological risks related to the use of demineralization technologies includes the following factors:

- Volume of WW related to 1 m^3 of produced permeate;
- TDS of WW, which indicates increasing of natural seawater salinity in a place of discharge;
- Specific salt disposal with WW referred to 1 m^3 of the permeate.

Type of membrane elements was considered as variable parameter both for membrane and combined schemes. Materials produced by Dow Chemical Company – Filmtec reverse osmosis and nanofiltration elements and Dowex ion exchange resins were chosen for the research due to their wide spread occurrence and high reliability. The limitation TDS ≤ 100 mg/dm^3 was applied to demineralized water entering ion exchange stage in a MB.

The calculations were performed for the capacity of 200 m^3/h by demineralized water using the computer-aided design systems for membrane (ROSA) and ion exchange (CADIX) processes developed by Dow Chemical Company [9,10].

Two types of elements Filmtec SW30XHR-400i and Filmtec SW30XLE-400i were chosen for the calculations of one-stage conventional membrane technologies. Their characteristics are listed in Table 2. The polycomposite polyamide membranes of the highest density are used in SW30XHR-400i elements. Therefore they are characterized by the highest salt rejection. Filmtec SW30XLE-400i elements are characterized by higher productivity at lower salt rejection. For this reason Filmtec SW30XLE-400i is positioned by manufacturer as the most cost-saving in the class of SW membranes. The technological scheme employing SW elements is based on a continuous separation process (Fig. 2).

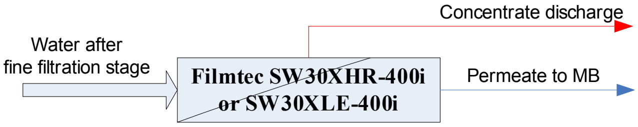

Fig. 2. Flowsheet of the seawater demineralization process employing high density membranes (SW).

Seawater demineralization technologies based on low and medium density membranes are designed as double-stage processes: the permeate of the first stage is source water for the second stage and the concentrate of the second stage returns into source water (Fig. 3).

The calculations were performed for three schemes applying five types of membrane elements: for the first stage — Filmtec BW30LE-440, NF90-400, NF270-400; for the second stage — Filmtec BW30-400, LE-400.

It should be noted that there is a significant difference between nanofiltration (NF) and reverse osmosis (BW, LE) membrane elements, consisting in different densities of the membranes — nanofiltration membranes have significantly lower density than reverse osmosis mem-

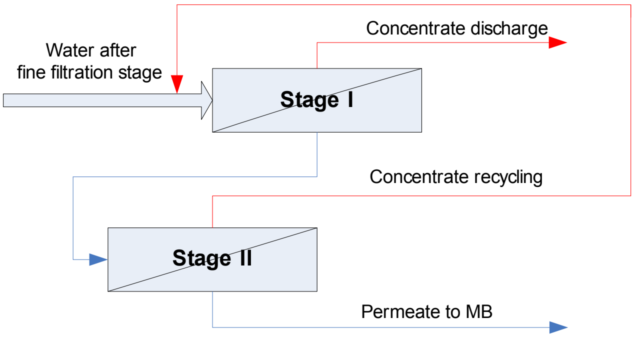

Fig. 3. Flowsheet of the seawater demineralization process employing low and medium density membranes.

Table 2
Characteristics of high density membrane elements (SW) [9,10]

Characteristic	Filmtec SW30XHR-400i	Filmtec SW30XLE-400i
Active area, m^2	37	37
Productivity on permeate, m^3/d	23	34
Salt rejection, %	99.8	99.7

branes. This simultaneously decreases salt rejection and working pressure. Among the elements considered the lowest density membrane is used in NF270-400 element and the highest density — in BW30-400.

The characteristics of membrane elements are presented in Table 3.

The calculations of double-stage combined technologies were performed for the reverse osmosis–ion exchange schemes. The configuration of the first stage was the same as in the double-stage reverse osmosis technologies, and the consequence H-cycle — OH-cycle with counter-flow UPCORE regeneration system was used for the second stage (Fig. 4). Characteristics of the ion-exchange resins used in the combined technology are given in Table 4.

The MB filter is considered as the final water demineralization stage. The permeates, obtained after different technologies, were used as initial water for the MB. TDS of water after the MB does not exceed 0.019 mg/dm^3 (conductivity — 0.2 μS/cm). Characteristics of the ion exchange resins used for the MB are given in Table 5.

4. Discussion of the results

The calculation results of the reverse osmosis stage of the seawater conditioning technology for a power

Table 3
Characteristics of the membrane elements of low and medium density [9,10]

Type of element	Active area (m^2)	Productivity on permeate (m^3/d)	Salt rejection (%)
Nanofiltration elements			
NF270-400	37	80	40–60
NF90-400	37	48.4	85–95
Reverse osmosis elements (for brackish water)			
BW30LE-440	41	44	99
BW30-400	37	40	99.5
LE-400	37	44	99.3

Table 4
Characteristics of the ion exchange resins [9,10]

Characteristic	Dowex UPCORE Mono C-600	Dowex UPCORE Mono A2-500
Type	Strong acid cation exchange resin	Strong base anion exchange resin, Type-II
Functional groups	Sulfonic acid	Dimethylethanolamine
Total exchange capacity, eq/dm^3	1.8	1.2
Moisture content, %	50–56	46–55
Grain form type	Monosphere	
Shipping weight, g/dm^3	800	690

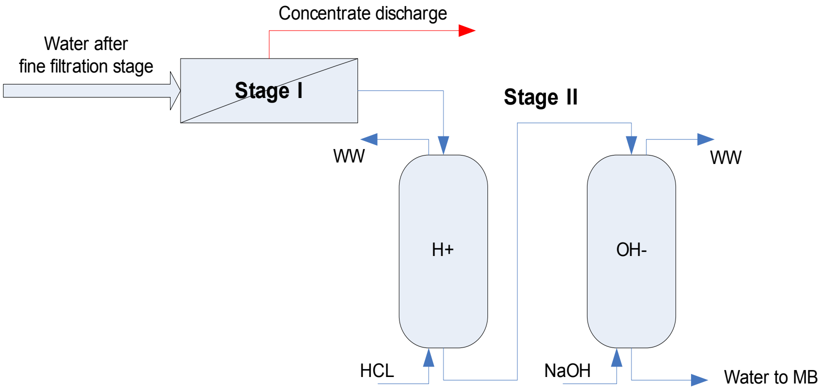

Fig. 4. Combined technology of seawater demineralization.

Table 5
Characteristics of the ion exchange resins used in the MB [9,10]

Characteristic	Dowex Monosphere 650C	Dowex Monosphere 550A
Type	Strong acid cation exchange resin	Strong base anion exchange resin, Type-I
Functional groups	Sulfonic acid	Quaternary amine
Total exchange capacity, eq/dm^3	2.0	1.1
Moisture content, %	46–51	55–65
Grain form type	Monosphere	
Shipping weight, g/dm^3	785	657
Volume ratio, cation exchanger/anion exchanger		1/1.7

producing industry employing high density membranes are presented in Table 6.

As follows from Table 6, the application of the SW30XHR-400 elements with a higher density membrane than in the SWXLE-400i allows obtaining permeate with more than 2 times lower salt content, however, in this case MOC are higher by 26%.

The calculation results of the reverse osmosis stage employing low and medium density membranes are presented in Table 7.

As follows from Table 7, water which passes the double-stage demineralization according to scheme No. 5 does not meet the criterion set for water before the MB (TDS ≤ 100 mg/dm^3). Hence, such a scheme cannot be used for a deep demineralization. At the same time TDS 156 mg/dm^3 meets the requirements for drinking water. Thus, this method can be used for producing potable water from seawater without a final remineralization stage. These data indicate that the self cost of potable water obtained by technology No. 5 is by 15–35% lower than the one for water obtained at the use of the traditional technologies (No. 1 and No. 2) even without accounting the remineralization costs.

The calculation results of the demineralization stage employing combined reverse osmosis–ion exchange technologies are presented in Table 8.

The analysis of the data presented in Table 8 indicates that proceeding to the nanofiltration elements in the combined technologies results in the growth of MOC more than 2.5 times with simultaneous deterioration of process' ecology. MOC of the combined technologies contrast with the values obtained for the membrane technologies (Tables 6, 7), however, the salt content in demineralized water is minimal.

The results of the calculations, obtained for different configurations of the seawater demineralization stage

Table 6
Economic and ecological parameters of the seawater demineralization stage employing high density membranes

Technology No.	Type of elements	MOC (\$/m^3)	TDS of the permeate (mg/dm^3)	Relative WW volume (m^3-WW/m^3-perm)	TDS of WW (g/dm^3)
1	SW30XHR-400i	0.134	30	1	29.94
2	SW30XLE-400i	0.106	83	1	29.89

Table 7
Economic and ecological parameters of the seawater demineralization stage employing low and medium density membranes

Technology No.	Stage	Type of elements	MOC (\$/m^3)	TDS of the permeate (mg/dm^3)	Relative WW volume (m^3-WW/m^3-perm.)	TDS of WW (g/dm^3)
3	I	BW30LE-440	0.115	423	1.17	27.80
	II	BW30-400		9		
4	I	NF90-400	0.091	1611	1.43	25.47
	II	LE-400		56		
5	I	NF270-400	0.089	5650	2.08	22.12
	II	LE-400		156		

Table 8
Economic and ecological parameters of the seawater demineralization stage employing combined technologies

Technology No.	Configuration	MOC ($\$/m^3$)	TDS of the permeate (mg/dm^3)	Relative WW volume (m^3-WW/m^3-perm.)	TDS of WW (g/dm^3)
6	BW30LE-440 IE	1.043	0.38	0.88	31.97
7	NF90-400 IE	2.781	0.38	1.27	26.21

Table 9
Economic and ecological parameters of the seawater demineralization stage with the application of different technologies employing final treatment stage in the MB

Technology No.	Technology parameters	MOC ($\$/m^3$)	TDS of WW (g/dm^3)	WW volume (m^3/h)
One-stage membrane technologies				
1	SW30XHR-400i	0.821	29.93	200
2	SW30XLE-400i	0.973	29.89	200
Double-stage membrane technologies				
3	BW30LE-440 BW30-400	0.700	27.79	234
4	NF90-400 – LE-400	0.863	25.47	286
Combined technologies				
6	BW30LE440 – IE	1.662	31.97	175
7	NF90-400 – IE	3.400	26.21	253

(Tables 6–8), were taken as the basis for estimation of the final treatment stage in MB. The summarized results are presented in Table 9.

It can be deduced from Table 9 that technology No. 3, based on the application of the medium density membranes BW30LE-440 – BW30-400, turned out to be the optimal for the seawater demineralization in a power producing industry. The use of this technology allows decreasing MOC by 15–30% compared to the conventional schemes utilizing high density membranes (No. 1 and No. 2). At the same time the use of combined technologies employing an ion exchange stage (No. 6 and No. 7) increases MOC by 60–80% compared to scheme No. 3. It should be noted that technology No. 4 based on the use of NF90-400 – LE-400 elements is close to the conventional schemes No. 1 and No. 2 by economic indicators.

The data on ecological evaluation of the considered technologies are presented in Fig. 5.

Summarizing the data in Fig. 5 and Table 9 it should be inferred that the optimal alternative in the context of

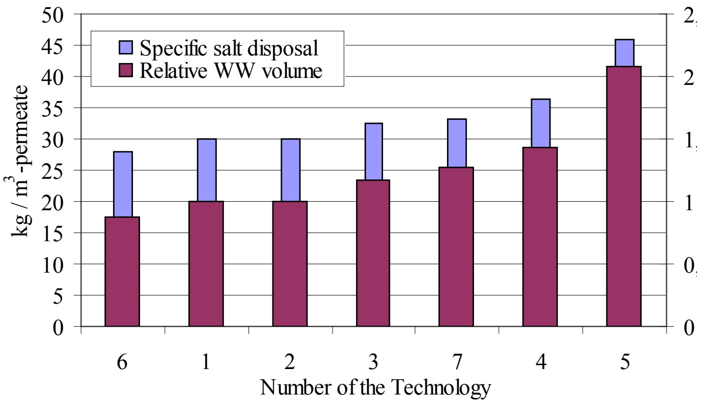

Fig. 5. Ecological evaluation of different seawater demineralization technologies.

ecology is absent among the considered technologies. Thus, WW discharged during the operation of scheme No. 4 (exceeding of seawater TDS in ~1.8 times) possess the lowest mineralization, however, the relative volume of WW (~1.5 m^3/m^3-perm.) and the specific salt disposal (>35 g/dm^3) are the highest. The most concentrated WW (exceeding of seawater TDS in ~2.3 times) is discharged in the volume of 175 m^3/h at operation of the combined technology No. 6. It should be noted that in the case of economically optimal technology No. 3 exceeding of seawater TDS is not beyond the limits of allowed value and on the reduced volume and salt discharge it takes middle position among considered schemes.

5. Conclusions

Thus, based on the results of the performed calculations it was determined that:

- The use of the double-stage reverse osmosis technology employing medium and low density membranes for the Black Sea water demineralization is economically expedient comparing with the conventional approach based on the use of the high density SW elements;
- The economically optimal technological scheme of the Black Sea water demineralization for a power producing industry includes a double-stage reverse osmosis with the Filmtec BW30LE-440 – BW30-400 medium density membranes and a final treatment in a mixed bed ion exchange filter. The operation costs for this technology are by 15–28% lower than for conventional technology.
- The water desalination of the Black Sea involving the double-stage membrane technology based on the NF-270-400 – LE-400 low density membranes allows obtaining potable water that does not require a final remineralization. In this case the operation costs can be decreased by 15–35% comparing with the conventional technology even without taking into account remineralization costs.

Abbreviations

BW — Designation of membranes and elements for brackish water desalination
CWP — Chemical water pretreatment
IE — Ion exchange
LE — Designation of membranes and elements for tap water desalination with low energy consumptions
MB — Mixed bed
MOC — Main operating costs
NF — Designation of nanofiltration membranes and elements
SW — Designation of membranes and elements for seawater desalination
TDS — Total dissolved solids
TW — Designation of membranes and elements for tap water desalination
WW — Wastewater

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