ELSEVIER

Desalination 205 (2007) 26–37

DESALINATION

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Four years of practical experience with an Integrated Membrane System (IMS) treating estuary water

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Received 2 February 2006; accepted 17 February 2006

Abstract

During the last decade of the 20th century an industrial water treatment plant was designed in order to supply the chemical plant of Dow in Terneuzen with high quality process and demin water. The Dutch Zeeland area is rich of water, but fresh water is scarce. In the pre-design of the plant several raw water sources were evaluated, including two sources of fresh water, effluent of an industrial WWTP, effluent of a communal WWTP and seawater. One of the main objectives of the plant's design was a reliable concept, using redundant sources and redundant production lines. Therefore the plant was designed to use different water sources and different treatment processes: seawater (from the Westerschelde estuary) and integrated membrane system (IMS) to produce demin water; fresh water and ion exchange to produce demin water; effluent industrial WWTP and media filtration to produce cooling tower supply water. The construction of the various water treatment lines started in 1998, with the plants being taken into operation in the year 2000. The design and construction were handled in a joint venture. The complete water treatment facilities produce an aggregate of 750 m^3/h demineralised water (demi water), 650 m^3/h cooling tower supply water and 1.050 m^3/h ultra-pure water (polished water). All water treatment facilities are now 100% owned by Evides. The IMS is equipped with micro strainers and microfiltration as pretreatment and a double pass RO-system to produce demin water. The raw water for the RO-train is taken from the cooling system from Dow. The source water for the cooling system is extracted via an open intake from the tidal Westerschelde estuary and is next to ships and barges pulling in and out of the dock, stirring up the bottom of the sea. The TDS level in the intake can fluctuate widely, depending on the season, the tides and the amount of water from the North Sea and the River

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Presented at EuroMed 2006 conference on Desalination Strategies in South Mediterranean Countries: Cooperation between Mediterranean Countries of Europe and the Southern Rim of the Mediterranean. Sponsored by the European Desalination Society and the University of Montpellier II, Montpellier, France, 21–25 May 2006.

Schelde. The conductivity of the water ranges between 30,000 and 45,000 µS/cm, and changes between these extremes in a matter of days. The temperature of the water is increased approximately 10°C in the cooling system. The main advantages of this water source were: intake and infrastructure already available: reduces costs for feed water intake; high temperature seawater: reduced seawater RO feed pressure; abundant availability: higher reliability. The use of preheated seawater from the tidal estuary as feed water to the IMS has resulted in many unsuspected problems in operation and maintenance of the IMS. Problems like corrosion and biofouling are enhanced by the higher temperature of the seawater. Another problem was the high turbidity loads in the water caused by the ships and barges at the seawater intake. The paper focuses on five years operational experience with the reverse osmosis train. The problems will be elaborated with operational and process trends and the solutions to solve the problems, in some cases extensive alterations of unit operations, will be presented. Based on the experiences in the past five years the choice of seawater as feed water for the RO-train is under reconsideration.

Keywords: Industrial water supply; DBFO; Demineralised water; Membrane technology; SWRO; IMS; Operations; Biofouling

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1. Introduction

In the mid-nineties of the last century, the Dow Chemical Company, one of the world's largest chemical companies, undertook a significant enlargement of the production capacity on her site in Terneuzen, The Netherlands. This enlarged production capacity necessitated a corresponding expansion of the energy production and cooling water facilities. This also presented an opportunity to replace a number of plants for the production of demineralised (demin) water, since high maintenance costs and energy consumption were making them inefficient and expensive to run so less appropriate to meet the future demands. The core concept for all changes and extensions was sustainability.

The changing water demand of Dow made it necessary to review the water supply in the whole area. Given the scarceness of fresh (surface) water in Zeeuws-Vlaanderen (southern part of the Netherlands), it is an absolutely precondition to optimise the use of this water. Evides Industriewater, a subsidiary of Evides NV, took part in this optimisation study together with her customer Dow. Evides is the supplier of drinking water in the provinces in the southwest of the Netherlands and the biggest supplier of industrial water in the Netherlands. Evides Industriewater owns and operates various plants in so-called DBFO concepts for industrial (process)water and the treatment of waste water. These plants are designed and built in-house. Evides Industriewater also manages and operates these plants on behalf of its customers.

In order to secure a reliable water supply in Zeeuws-Vlaanderen, Evides Industriewater conducted studies into the exploitability of its various water sources in the region as well as the option of water reuse. Among the possibilities explored for production of demin water were the use of brackish groundwater, seawater, effluent from the municipal waste water treatment plant, river water from the river Maas (Biesbosch water) and saline effluent from Dow's own wastewater treatment plant. In addition, the recycling of treated sweet wastewater for use as cooling water was another possible option that was studied. These studies resulted in the construction of water treatment facilities that produce various kinds of water from six different water sources [1].

The main objective of the plant's design was a reliable concept, using redundant sources and redundant production lines. Therefore the plant was designed to use different water sources and different treatment processes to deliver the same water quality (Fig. 1).

The desalination of the Westerschelde water takes place in an Integrated Membrane System (IMS) plant, which is located in a new building next to the site of Dow. This building, called the

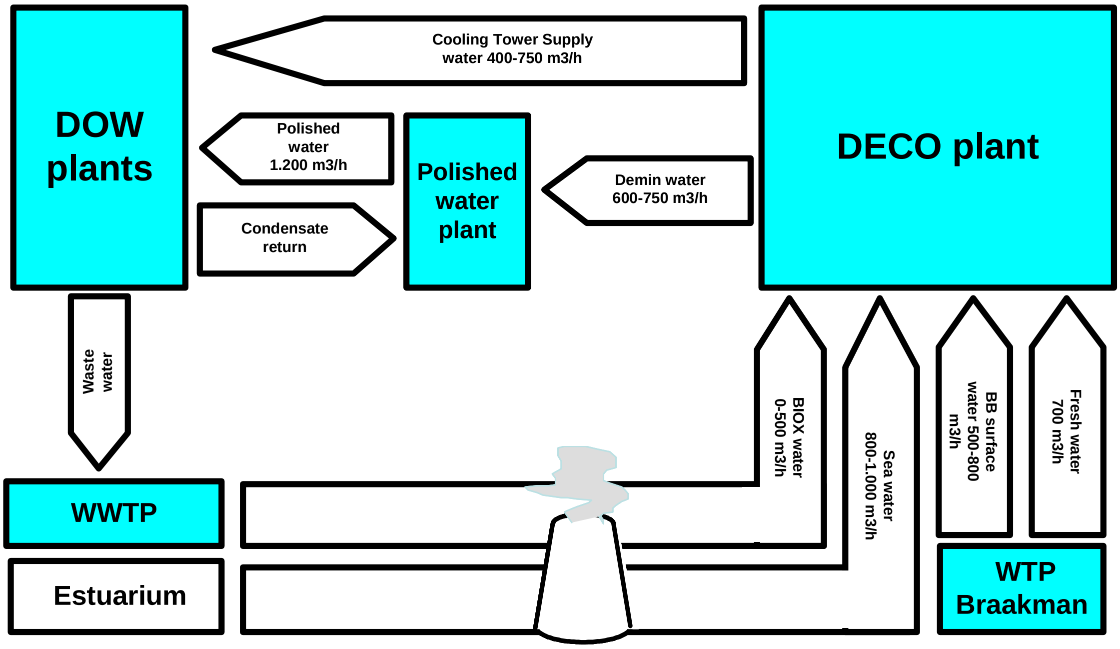

Fig. 1. Overview of water flows.

Deco plant, contains next to the IMS also production lines with ion exchange and multimedia filters to treat the other water sources.

The construction of the various water treatment installations started in 1998, with the plant being taken into operation in 2000. The design and construction were handled in a joint venture. All these water treatment facilities are currently 100% owned by Evides Industriewater. The redundancy of the water treatment system was expanded in 2004 through the construction of an additional ion exchange line (IX). The complete water treatment facility produces an aggregate of 750 m^3/h demineralised water (demin water), 750 m^3/h cooling tower supply water (cooling water) and 1.200 m^3/h ultra-pure water (polished water) [2].

In this paper the four years of practical experience with the IMS will be described. It contains educational information, which the authors would like to share with the reader. After an introduction showing the feed water quality and process design details the operational problems caused by the design will be outlined and some of the solutions will be described and discussed.

2. Water quality

The water quality of the feed water from the Westerschelde estuary is heavily fluctuating due to tides and seasonal water quality changes. The water analysis of the feed water is provided in Table 1 (from the year 2002 till date). During the operation, the preheated seawater temperature varies from 15°C in January to 33°C in August. The conductivity of the water ranges between 25,000 and 40,000 µS/cm and changes between these extremes in a matter of days.

The temperature of the feed water is in average increased with approximately 10°C in the cooling system of Dow. In the past the heated water was directly discharged after usage, but since the start-up of the IMS a side stream of the cooling water,

Table 1
IMS feed water characteristics

	Minimum	Average	Maximum
Temperature, °C	14	23	33
Suspended solids, mg/l	8	19	60
pH	8.00	8.08	8.23
EC (20°C), µS/cm	26,950	32,871	37,025
Bicarbonate, mg/l HCO_3	146	174	194
Chlorides, mg/l Cl	9,116	12,818	15,358
Sulphate, mg/l SO_4	801	1,546	2,052
Sodium, mg/l Na	4,894	7,123	8,517
Potassium, mg/l K	206	260	297
Calcium, mg/l Ca	255	296	323
Magnesium, mg/l Mg	682	873	1,009
Ammonium, mg/l NH_4	0.12	0.22	0.30
Nitrogen, Kjeldahl, mg/l N	0.39	0.76	1.48
Nitrate, mg/l NO_3	3.36	5.62	8.57
Total phosphate, mg/l P	0.07	0.12	0.21
Silicate, mg/l Si	0.44	1.48	3.01
Iron, µg/l Fe	79	137	194
Manganese, µg/l Mn	8	12	16
Barium, µg/l Ba	13	14	15
Strontium, µg/l Sr	4,015	4,852	5,520
Fluoride, mg/l F	0.70	0.97	1.24
Total organic carbon (TOC), mg/l C	1.32	2.13	3.21
Coulour intens. Pt/Co-schaal, mg/l Pt	5.82	9.96	16.27

approximately 1.000 m^3/h, is lead via a pipe line to feed the IMS in the Deco plant. The feed water is extracted via an open intake and a 5 mm screen.

The expected advantages of the feed water source were:

- Intake and infrastructure already exist: which reduces costs for feed water intake;
- Elevated temperature seawater: enhancing fluxes and reducing RO feed pressure and enhancing energy conservation;
- Abundant availability: higher reliability of the water source.

Based upon the water quality the characteristics of Table 1, the feed water does not show many disadvantages. However in practice it is a dynamic mixture of 2/3 seawater and 1/3 sweet river water and still contains after the pulse chlorination (BAT protocol) in the cooling tower sufficient amounts of nutrients to promote biofouling growth.

The total dissolved solids (TDS) level in the feed water can fluctuate dramatically, depending on the tides: the amount of water from the North Sea and the River Schelde. Furthermore the intake is next to a harbour dock with ships and barges pulling in and out of the dock, stirring up the bottom of the estuary.

3. The desalination process

The water treatment plant consists of the following serial units (Fig. 2):

- Rotating micro screens (150 micron)
- Microfiltration (CMF)
- MF permeate reservoir
- Seawater reverse osmosis (SWRO)

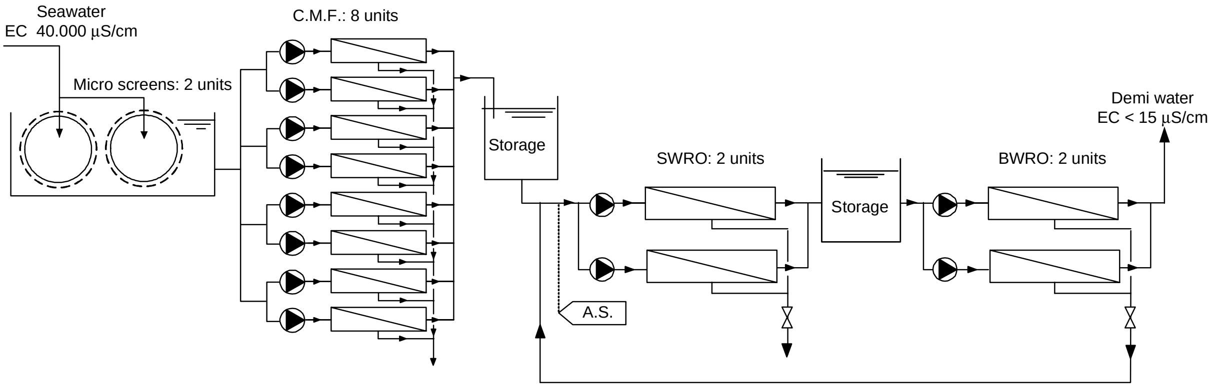

Fig. 2. Process flow diagram of the IMS.

- SWRO permeate reservoir
- Brackish water reverse osmosis (BWRO)
- Parallel a cleaning facility for chemical flushes and CIP cleaning

The pre-treatment of the IMS consists of two rotating micro screens of 150 µm. These screens serve mainly to remove the larger suspended particles from the water. After the screens, the water is fed into a basement which stores the feed water and eight submerged pumps feeding the continuous microfiltration (CMF) units. Microfiltration or ultrafiltration is considered to be the best option for pre-treatment of the feed water for the RO process, since it will remove the suspended solids completely, remove algae, will disinfect the water and has a small footprint.

It is said that microfiltration as pre-treatment typically enables the RO flux to be increased by 20%, and it will decrease the RO fouling. Compared to conventional pretreatment, microfiltration has the ability to handle high and variable loads and the filtrated water shows 60–70% improvement in turbidity and 70–80% improvement in silt density index measurements (SDI < 3). The CMF units were designed to filter 700–750 m^3/h at a temperature range of min.15 to max 35°C. (7 units, 1 standby). Each unit is equipped with 78 pressure vessels with polypropylene (PP) hollow fibre membranes, placed in a vertical position and operated according to the dead-end principle.

The units were programmed for a backwash every 20 min (air via lumen to shell in combination with shell sweep). Next to the backwash a cleaning in place (CIP) with enhanced caustic agent (every 3 d) and a CIP with sulphuric acid (every 14 d) was required. The designed fluxes were 110 $l/m^2.h$ (brut) and 86 $l/m^2.h$ (net) based on the internal surface of the membranes. The service time was designed to be 85%.

The CMF permeate is desalinated in two water treatment lines consisting of two SWRO units and two BWRO units.

The two SWRO units are equipped with high pressure pumps with an energy recovery system (Pelton wheel) and consist of 44 pressure vessels loaded with 6 Dow/FilmTec SW30 membranes each. The designed permeate capacity of the SWRO equals 210 m^3/h per unit. The SWRO operates at a recovery rate of 50–55%. Anti scalant is dosed to the feed stream of the SWRO with a concentration of 3–4 ppm. The SWRO permeate flows into a reservoir; the SWRO concentrate is directly discharged into the Westerschelde.

The second stage of the desalination process is treatment of the SWRO permeate within the BWRO units. The two BWRO units consist each of a two-stage design, first array compiling 16 pressure vessels, second array compiling 6 pressure vessels. The vessels in both arrays contain 6 Dow/FilmTec BW30 membranes. The designed permeate capacity of the BWRO equals 175 m^3/h per unit. The BWRO operates at a recovery rate of 85%. No anti scalant nor other chemicals are dosed to the feed stream. Since the feed water is permeate water of the SWRO containing mainly monovalent ions. The permeate of the BWRO has a conductivity of 10–15 µS/cm. This water is mixed with demin water originating from the ion exchange process and consecutively supplied to Dow. The concentrate of the BWRO is mixed with the pretreated seawater and fed to the SWRO, hence reducing the salt content of the saline feed to the SWRO by approximately 8%.

4. Operational problems

The feed water source, originating from the biological active Westerschelde estuary, results in a variable (high) organic load. The conditioning regime of the once through cooling water system is based on alternating pulse chlorination according to the European Best Available Technology. This regime delivers discontinuously acute toxicity in the first half of the cooling system but its effluent, which is reused to feed the IMS only contains a chronical toxicity. Problems like corrosion and biofouling are enhanced by the higher temperature of this feed water coming from the cooling system. Another problem was the high turbidity loads in the water caused by the ships and barges at the seawater intake.

Some variations in the quality of the feed water were taken into account in the IMS design but generally it has had many unforeseen problems in operation and maintenance. Some disadvantages showed directly after startup of the plant, others came about in time, like: construction failures, insufficient material selection, water hammering, insufficient cleaning processes, high maintenance and poor process data processing. The following items will be further addressed:

- Membrane performance
- Biofouling
- Corrosion

4.1. Membrane performance

The bottleneck is the output of the CMF membrane units which is limiting the total plant capacity. Due to the optimistic flux assumption, the amount of filtration area is too little to treat a sufficient amount of feed water.

The variable suspended solids and organic load of the feed water resulted in a higher CIP frequency and lower online time of the CMF units than expected. The fluxes are based upon a short pilot trial period of 6 weeks on sophisticated cooling water with acute toxic conditions. A similar membrane pilot equipped with UF modules ran a period of 6 months.

Table 2 shows data of the full-scale operation, the design and the practical operational conditions of the process units.

The operational practice differs largely from the design parameters, this resulted in production capacity loss which could not be compensated within the IMS. Even a lot of extra efforts, like intensive CIP cleaning were not sufficient to compensate this loss. Inside the plant the turbidity of the feed water and filtrate after screens is measured with an automatic device. Fig. 3 shows one typical year mid 2004–mid 2005 of the turbidity and the SDI_{15} of the CMF permeate water. The SDI_{15} is typically below 4, instead of below 3. During the operation periodically pressure decay tests are performed to secure membrane integrity.

Table 2
Design and practical operational conditions of the CMF

Memcor CMF 78M10C	Design	Practice
Units in operation	7 of 8	8 of 8
Capacity per unit, m^3/h	110	80
Online time units, %	85	78
Permeability, $l/m^2.h.bar$	300	100–150

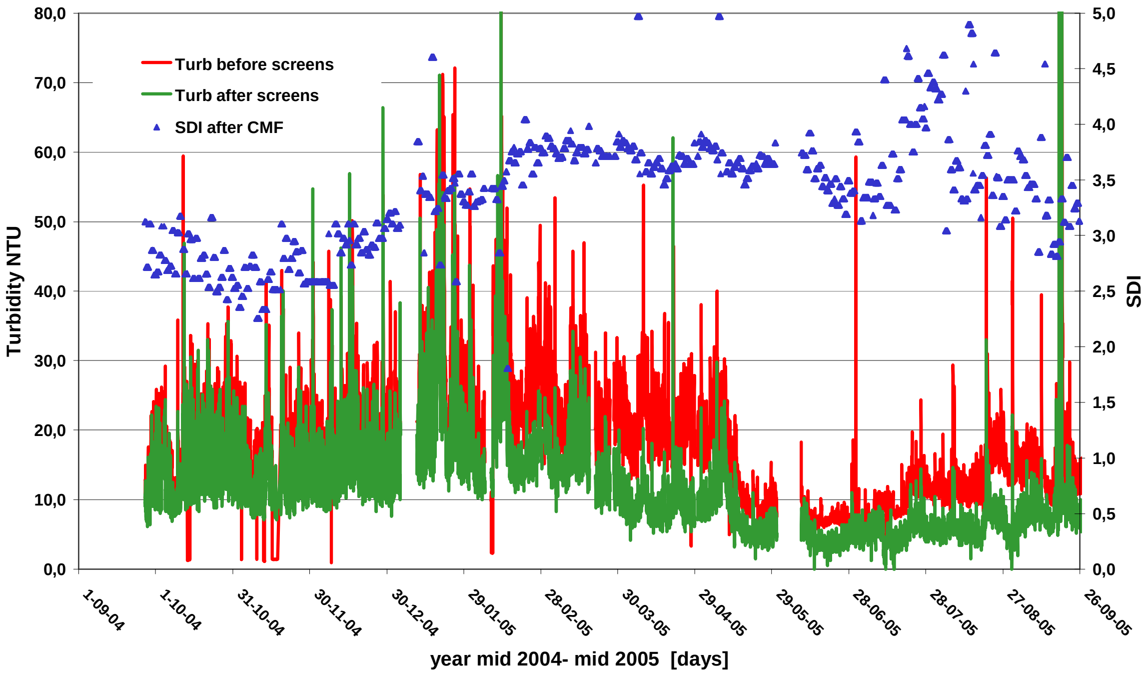

Fig. 3. Feed water turbidity and CMF permeate SDI values.

The presence of (bio)fouling is evident when CMF membranes were autopsied (Fig. 4). Membrane replacement was the only alternative. Typically the SDI of the permeate came higher after replacement. Because of the limitations Evides upgraded the CMF unit in the year 2004: the valve control, the piping, the system automation and especially new CIP systems and applied CIP chemicals to improve the CMF system performance.

The CMF performance improved substantially, however it was impossible to improve the output in such an order that the design specification were met.

The SWRO performance was reduced in capacity by the limited CMF capacity, but furthermore the SWRO had to deal with heavy biofouling due to the lack of disinfection within the IMS. Table 3 shows the design and the practical operational conditions of the SWRO process unit. The performance of the RO units is monitored via the membrane transfer coefficient (MTC), normalised salt passage (NSP) and normalised pressure drop (NPD) [3]. The MTC and NPD of one of the SWRO units are shown in Fig. 5.

Fig. 4. Fouled CMF membrane.

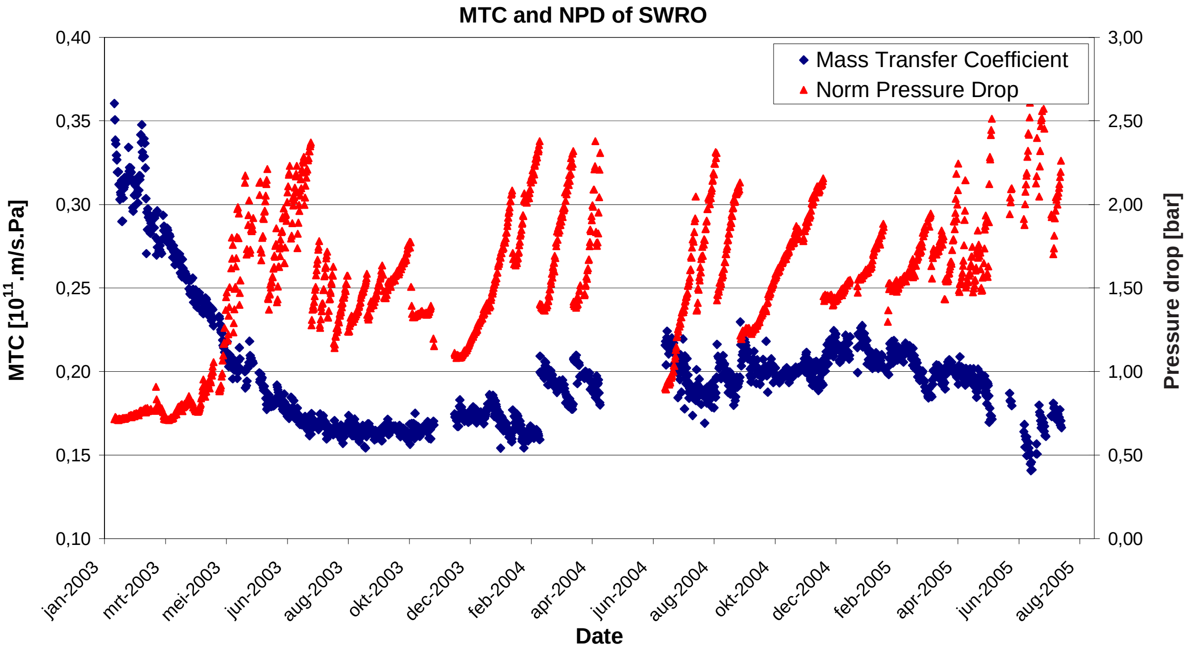

Fig. 5. Mass transfer coefficient and NPD of one SWRO.

Table 3
Design and practical operational conditions of the SWRO

SWRO	Design	Practice
Capacity per unit, m^3/h	210 (420 total)	150–175 (300 total)
Units in operation	2 of 2	1 of 2
Recovery, %	50–55	50–55
Pressure, bar	55–70	55–70
Temperature, ºC	15–35	15–35
Flux, l/m^2h	22	17–20

Table 4
Design and practical operational conditions of the BWRO

BWRO	Design	Practice
Capacity per unit, m^3/h	175 (350 total)	150 (300 total)
Units in operation	2 of 2	1 of 2
Recovery, %	80–85	80–85
Pressure, bar	10–15	10–15
Temperature, ºC	15–35	15–35
Flux, l/m^2h	25–30	25

In order to obtain a complete picture of the IMS also the performance of the BWRO is compiled in Table 4. It shows the design and the practical operational conditions of the BWRO process unit. The performance of the BWRO was not influenced by biofouling but by the limited productivity of the SWRO.

4.2. Biofouling

Because of the higher temperature and the presence of nutrients the permeate of the CMF systems is a perfect breeding ground for biomass. The formation of biofilm within the IMS is reducing the operational hours of the full plant and specifically the SWRO units. The biofilm formation

Fig. 6. Fouled SWRO membrane.

rate typically increases dramatically during spring and summertime. This causes rapid pressure drop over the membranes, resulting in flux loss. After autopsy of the membrane module showing filamentous bacteria, slime and some inorganic materials it was clear that the main cause for underperformances was biofouling (Fig. 6).

Studying the CIP protocol and the CIP equipment of the SWRO a number of limitations of the design came across. These limitations were found in the cross flow velocity, the temperature, the tank volume and process control. In the year 2004 a new CIP system was designed and installed in the Deco plant serving the SWRO and the BWRO units.

Via this improvement the end result of the CIP was optimized: lowering the pressure drop over the system, improving the MTC and lowering the CIP frequency. Fig. 7a shows a typical CIP before the year 2004 and Fig. 7b CIP after the upgrade of the CIP system. Most CIP's are performed with hot caustic solution at a pH of 11–12 followed by an acidic solution at a pH of 2.

This CIP regime stopped the continuous rise of the pressure drop baseline and levelled it in to a sustainable level of 1.3 bar after a CIP. In order to improve the CIP performance special CIP cleaning agents were also used like sodium dodecyl sulphate and formulated products coming from specialized companies. The special cleaning agents showed extra performance.

Apart from this successful implemented improvement, disinfection of the feed water (to the SWRO units) remains requiring to obtain an ac-

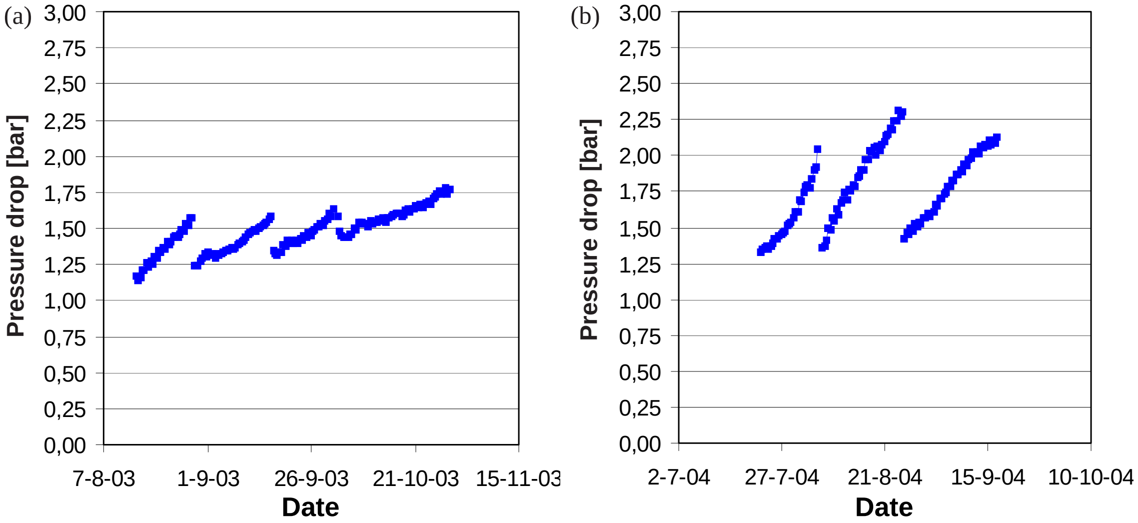

Fig. 7. Cleaning efficiency (a) before upgrade of CIP and (b) after upgrade of CIP.

ceptable CIP frequency during the spring and summer period. For this reason a 2,2-dibromo-3-nitrilopropionamide (DBNPA) disinfection agent is applied in the process in order to obtain a stable pressure drop over the SWRO unit. Fig. 8 shows the typical effect of the inline dosage of 50 ppm for 30 min (red line) on the NPD development. The dosage leveled the NPD of the SWRO for a period of approximately 36 h. After that period the NPD graph picks up its original gradient. The application of DBNPA is still under evaluation, but the fist results show a positive effect.

Unfortunately the application of DBNPA in the Netherlands is restricted and the use within membrane units treating water is limited via the borders of legislation.

4.3. Corrosion

The combination of preheated seawater and aerobic has resulted in many under anticipated maintenance problems and extra costs. The process units have a large number of (inter-) connections, which contain gaps ideally fit for sludge accumulation. These gaps filled with sludge are an ideal environment for anaerobic corrosion. Even units constructed out of stainless or duplex steel suffer under the feed water conditions. For example severe crevice corrosion is experienced on many flanges and gasket joints throughout the plant. The temperature is elevated above the upper limit for crevice corrosion of duplex material. The elimination of crevices in all the elements of process units was required to reduce the corrosion in order to maintain the units is good shape.

The individual submersible feed pumps of the CMF units require additional sacrificial anodes for galvanic protection. This is effective. However the impeller op the pump is heavily hit by cavitation due to the water and the wide range of operational flows required operating a CMF unit. This requires replacement every 6 months. Due to the frequent valve operation of the CMF unit it is very important to have a proper gasket selection to avoid valve malfunctioning.

The micro screens are corroding heavily under the conditions, like the duplex shaft, the fasteners (nuts and bolts) of the screens and the screen material (Figs. 9 and 10). Non-metallic materials are the only alternative to deal with this kind of feed

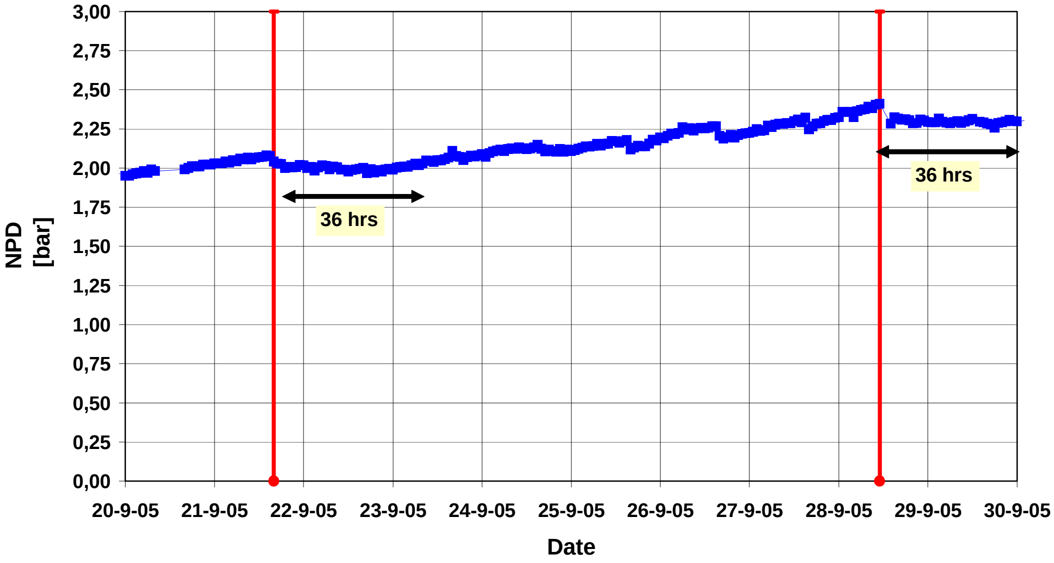

Fig. 8. The effect of DBNPA on the gradient of the NPD of SWRO.

Fig. 9. Corrosion of rotating screens.

Fig. 10. Detail of nuts and bolts of rotating screens.

water. At this stage the permanent rinse with (fresh) water of units is the selected option in order to avoid sludge accumulation and preventing anaerobic corrosion.

5. Conclusion

Initially the expectation was raised that the use of seawater would bear many advantages. However in practise the joint venture running the plant has experienced many difficulties caused by this very feed water source: estuary water coming from an once-through cooling water system. Additionally, the design of the IMS was based on far too optimistic performance parameters, which have not been properly evaluated by means of an adequately long pilot study. Directly after start-up of the IMS plant the engineering failures and operational malfunctions surfaced. Other disadvantages came about in time, like insufficient membrane cleaning processes, corrosion, limited process automation and poor process data processing. As a result the design capacity of the IMS (3 million m^3/y of demin water) has never been accomplished.

After the participating OEM left the joint venture, Evides took over the full responsibility running the plant to secure a reliable water supply to Dow Company. The team spirit of the Evides operation group, the redundancy in treatment plants and the availability of six different water sources were the keys to success the past four years. Nevertheless, the loss of production capacity of the IMS had to be corrected via an improvement of performance. Therefore in the year 2004 many modifications to the IMS were made. Evides designed and executed all modifications to the IMS plant and managed to reduce the downtime of the IMS plant spectacularly. The modifications and extensive alterations of the units resulted in an increase of the plant capacity to 2 million m^3/y. Though it proved impossible to restore the capacity of the CMF to its design level, the CMF system currently produces permeate of a sufficiently consistent quantity and quality of SDI_{15} values between 3–4; regardless of the variable feed water quality.

The efficiency of the CIP processes is improved after the installation of new CIP units, allowing optimal cross flow velocity, chemical and temperature control and tank volume. Substantial alterations of the IMS process control and data processing resulted in continuously monitored process and hence a better performance of the membranes.

Normalized process data are necessary to monitor membrane performance and to be able to deal with dynamic processes like biofouling.

Biofouling remains to be an issue in the IMS, due to the feed water source, the cooling water conditioning regime and the limited means of disinfection. It necessitates ongoing operational attention and CIP cleaning. It is therefore likely that the application of in-line disinfection products, such as DBNPA, is required and thus need to be investigated.

As a result of the in-depth studies highlighted in this paper, Evides and its partners gained a lot of operational experiences and confidence with membrane units in the last four years.

In spite of the improvements and retrofits as well as the optimisation of the process, the cost of maintenance, the applied chemicals and energy of the IMS is considerably higher than expected. Therefore the feed water source of the IMS is under reconsideration. Currently more reliable water sources are evaluated, like anaerobic groundwater and sweet tertiary wastewater. The progress will be announced on a later date.

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