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Pretreatment approach for the high turbid seawater using decanter centrifuge-microfiltration hybrid system

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ABSTRACT

The quality of seawater is different at different locations in Kuwait. The seawater quality in the Sabiya Power Generation and Water Desalination Plant (SPDP) is highly turbid due to the high silt and sand content and this often results in major disruptions to the plant's operations and requires frequent unscheduled maintenance. In spite of the availability of the space required for the installation of additional desalination and power generation units within the Plant, the seawater quality at that location limits full use of such units. This study aimed at assessing the viability of enhancing seawater quality for thermal and membrane-based desalination processes at SPDP using an integrated pilot-scale decanter centrifuge/microfiltration (MF) system. The study concluded that (1) polyelectrolyte dosing along with clarifier tanks placed before the decanter centrifuge unit were very effective in stabilizing the quality of the seawater feed; (2) the decanter centrifuge system is a viable mechanical process for improving the quality of SPDP's seawater feed; (3) the efficiency of the decanter unit reached 99.6%; (4) the turbidity values obtained immediately after the decanter unit were lower than 5 NTU, however, it was very difficult to obtain silt density index (SDI) measures below 6; (5) conversely, SDI values lower than 3.5 were achieved with further treatment utilizing MF system which is an acceptable level that facilitates safe use of the seawater as feed for membrane and thermal desalination units as well as for power generation equipment.

Keywords: Decanting centrifuge; Microfiltration; Silt; Sand; Silt density index; Water quality; Turbidity

1. Introduction

Desalination is a solution to water shortages in many parts of the world and it remains to be the most viable provider of freshwater in Kuwait and the Arabian Gulf Cooperation Council (GCC) countries. All indications have suggested that desalination technology will play a major role in providing potable water to coastal cities and industries. Among these desalination methods, multistage flash (MSF) and reverse osmosis (RO) are the most widely used. MSF is a thermal distillation process that is commonly used for the production of desalinated water globally and more specifically in Kuwait and the GCC countries. However, the process is usually coupled with power generation and is plagued by high capital and operational cost as well as low recovery ratios when compared to RO. RO has become increasingly popular as an alternative seawater desalination technology for economic reasons as it produces freshwater at a low cost due to the continuous improvement in RO membranes. Furthermore, RO

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can be used for treating brackish groundwater and municipal wastewater [1,2]. However, the use of RO seawater desalination is limited by two major drawbacks, namely, biofouling and scaling. Additionally, the success of this method is highly dependent on the seawater quality.

Seven seawater desalination plants exist in Kuwait and these are located in Shuwaikh, Shuaiba North, Shuaiba South, Doha East, Doha West, Az-Zoor South, and Sabiya with production capacities of 49.5 (19.5 MSF and 30 RO), 45 (MSF), 36 (MSF), 42 (MSF), 110.4 (MSF), 145.2 (115.2 MSF and 30 RO), and 100 (MSF) million imperial gallon per day (MIGPD), respectively [3]. The Sabiya Power Generation and Water Desalination Plant (SPDP) is the largest power and water production station in Kuwait in terms of the available free area for future expansion. The available free area at SPDP is expected to provide an invaluable opportunity for installing RO units, given the limited space of Kuwait's shores for the construction/expansion of water desalination facilities. However, the seawater feed at the SPDP contains high concentrations of silt and sand which affects the performance and maintenance schedules of the power generation and water desalination units. The seawater turbidity at SPDP is very high and it is very difficult to obtain silt density index (SDI) readings below 6 which is an indicator of the poor quality of the seawater feed for RO desalination units (good quality seawater feed for RO desalination units should not exceed 5). Therefore, seawater with such quality cannot be used for RO desalination without stringent pretreatment to reduce the feed water's silt and sand content. Another indicator for feed water to be used in RO desalination is an acceptable nephelometric turbidity unit (NTU) of 1–5 [4]. Furthermore, the quality of seawater feed at SPDP is currently causing serious damages to the thermal desalination units and to the power generation turbines. The turbidity values of the seawater intake at SPDP can reach values that exceed 985 NTU which renders the SPDP site unusable for hybrid MSF desalination-RO due to the poor seawater quality.

In addition to the high annual cost of maintaining the Station's units, dredging of the seawater intake is carried out at SPDP on a yearly basis to prevent blockage of the intake by heavy silt accumulations. Fig. 1 shows images of turbid seawater at the SDPI site and the dredging process inside the seawater intake at the Sabiya Power Generation and Water Desalination Plant.

Several techniques are commonly used to treat turbid seawater and seawater with high algal blooms. Kim et al. [5] developed a novel fiber filter integrated with an ultrafiltration (UF) system to pretreat highly turbid seawater. Even during periods of high turbidity where the seawater reaches levels of 52 NTU, this integrated system was effective in supplying feed water of suitable quality (SDI of less than 3) for RO membranes. This pretreatment system has a small footprint and low chemical and energy usage, rendering it cost-effective. Zhang et al. [6] evaluated the potentials of the UF system in dead-end mode before RO for high turbidity seawater desalination. The UF testing system was supplied directly with high turbidity seawater over 50 d of operation, and then switched to seawater coagulation prior to the UF. The study found that the UF system offered excellent and consistent quality permeate water regardless of the feed water; the SDI was kept below 3, which met the requirement for RO intake water quality. The water flux ranged from 50 to 100 L/m^{2}h with and without the addition of a coagulant. Raw seawater coagulation further helped to enhance UF membrane flux and filtered seawater supply in a steady-state situation. Cha et al. [7] developed a new process of meshed tube filtration (MTF) as a low-energy seawater pretreatment process that withstands algal blooms. The algal matter was coagulated and cycled by aeration in the MTF system, which was made up of cylindrical polypropylene meshed tubes with ciliary ends that could effectively retain coagulated algae. By regulating the coagulant dose and aeration rate, the ability of the MTF process to remove algal cells was greatly improved. In typical RO plants, this technique could potentially replace the dissolved air flotation (DAF) process. The results showed that MTF removed a large number of algal cells and reduced turbidity, except for a small amount of algal organic matter (AOM). Lee et al. studied the permeate quality, membrane performance, and microbial community in gravity-driven microfiltration (GDM) reactor and biofiltration (BF) + GDM reactor as a pretreatment process for RO desalination [8]. The addition of a BF column was more effective in eliminating soluble organic compounds through biosorption/biodegradation, resulting in better permeate quality from BF + GDM and lower RO fouling than GDM. The granular activated carbon media in BF increased the scaling organic material removal in BF + GDM when compared to the biofilm-saturated anthracite media. Although BF + GDM collected fewer organic compounds and microbial organisms on the membrane, its permeate flux was 10%–20% percent lower than GDM. The cost analysis revealed that BF + GDM-RO has 5.2% lower operational cost and 1.5% lower water production cost than GDM-RO.

The simplest and most direct treatment process is to separate the silt and sand from seawater by using accelerated gravitational forces through rapid rotation known as centrifugation/hydrocyclone [9,10]. Hydrocyclone belongs to a class of washing classified devices that separate solids from a fluid stream [11,12]. The hydrocyclone converts the initially linear motion of the seawater into continuously varying angular motion, thereby subjecting the dispersed particulates to centrifugal acceleration and enhancing the rate of settling of silt and/or sand according to their size, density, and shape. A recent study by Farghaly et al. [13] witnessed a drastic reduction in the NTU level from ~500 to ~16 by combining the hydrocyclone–electrocoagulation integrated system for the treatment of industrial wastewater. This recent study for removing or reducing silt and/or sand from SPDP's seawater intake using hydrocyclone system with different cone diameters of 10, 8 and 6 mm indicated that the system was able to remove/reduce silt and/or sand only by an average of 10%, 16%, and 8.5%, respectively [14]. This implies that the hydrocyclone system was inefficient in reducing the silt and/or sand from the seawater intake at the Sabiya station to the desired level. Generally, centrifuges follow the centrifugation principle and are used to separate different solids from the liquid phase. Centrifuges are of the basket, disc, nozzle bowl, solid bowl, chamber bowl, pusher, and decanter

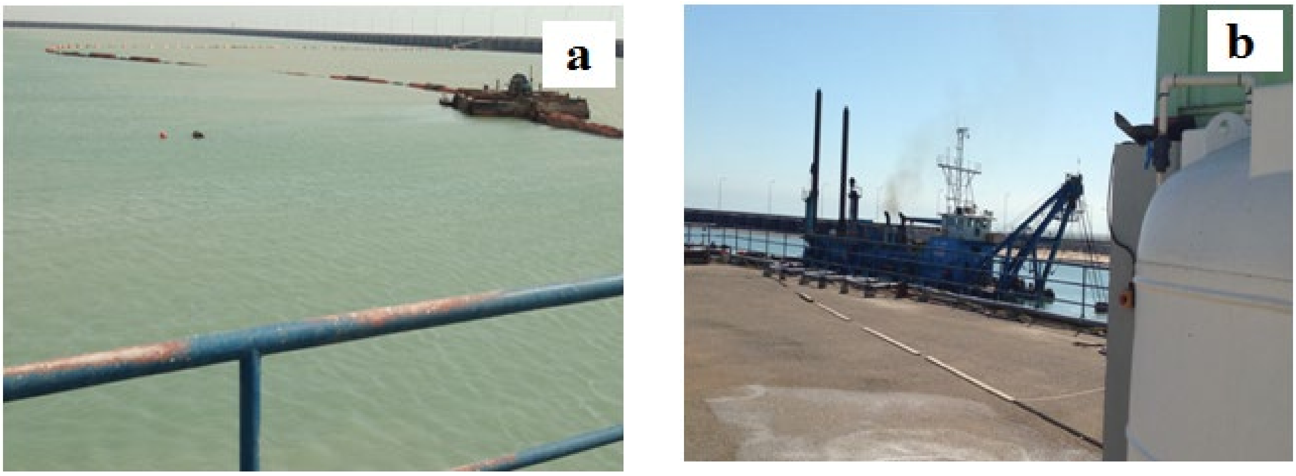

Fig. 1. (a) Turbid seawater at SDPI's site and (b) dredging of the seawater intake inside the Sabiya Power Generation and Water Desalination Plant.

solid bowl types and different theories on the separation of the solid phase from the liquid phase are described in detail in the literature [15–18]. A previous study carried out by KISR conducted tests using a decanter centrifuge system for removing/reducing silt and/or sand from seawater at the SPDP site. Results showed that the reduction of silt and/or sand reached values of around 60% to 90% using chemical dosing and clarifier tanks placed before the decanter unit. The chemicals used in the aforementioned study were ferric sulfate as a coagulant and a cationic polymer at a ratio of 1:2 [14].

Traditionally, in high turbidity seawater areas such as deltas and gulfs, the intake of seawater will require additional pretreatment before introduction to the desalination system, as it prevents damaging the systems and reduces long-term maintenance. The main aim of this study is to assess the viability of enhancing seawater quality for thermal and membrane desalination processes at SPDP using a pilot-scale decanter centrifuge unit followed by a microfiltration (MF) system. Decanter centrifuge system has been only previously applied for the separate components of different densities within water/sewage treatment, processing chemicals, oil production, etc. The new application of decanter centrifuge in seawater pretreatment is part of the novelty of this study that utilizes polyelectrolyte dosing, clarification through clarifier tanks, and centrifugation in a decanter centrifuge followed by microfiltration prior to the introduction of the seawater intake to the desalination plant. This study aimed at assessing and validating the viability of using a hybrid system decanter centrifuge-MF process as a water treatment system for treating highly-turbid seawater for the subsequent desalting process such as RO. Also, the study aimed at evaluating the step-wise improvements in the treatment of turbid seawater starting from clarifier tanks to the decanter centrifuge-MF hybrid system. The tests on the aforementioned hybrid process were limited in number and were just enough to draw clear and reasonable conclusions on the separation performance of the proposed system in such an application. The experiments performed on the said hybrid system were conducted in a batch mode.

2. Experimental work

2.1. Experimental setup

The process diagram of the decanter centrifugation system is presented in Fig. 2 and more details are provided in the previously filed US patent [19]. The turbid seawater feed was directly collected from SPDP's seawater intake using a submersible pump passing through four clarifier tanks and a strainer before being transferred to the decanter centrifugation feed tank. Due to instability of the feed water quality at SPDP, four clarifier tanks with a capacity of 1 m^3 each were designed, constructed, and successfully installed (Fig. 3). These tanks were designed to stabilize the quality of the feed and to increase the contact time for the coagulation/flocculation process. The tank specifications are as follows:

- The tanks were fabricated using the chemicals-resistant water-repellent natural color polypropylene.
- The tanks are of 1 m^3 each, 1,000 mm × 1,000 mm × 1,000 mm (H × W × L).
- The tanks walls and bottom are 8 mm in thickness.
- The inner separators are of 8 mm thickness; cover and flaps are of 6 mm thickness.
- The inner separators and flaps are fixed.
- The tank bottoms are slanted with a difference of 50 mm from one side ending at zero on the opposite side.
- The angle at the inner lower part of the vertical flaps is 45°.
- The flow absorbent sheet is placed at 100 mm from the top edge of the tank.
- The bottom layers of all of the tanks contain the lowest points 2-in. drainage connections that end with a flange for further connection.
- The first three tanks contain 4-in. inlet and outlet connections that end with a flange for further connections. The inlet and outlet connections are positioned at 100 mm from the top.
- The fourth tank contains 4-in. inlet and outlet connections that end with a flange for further connection.

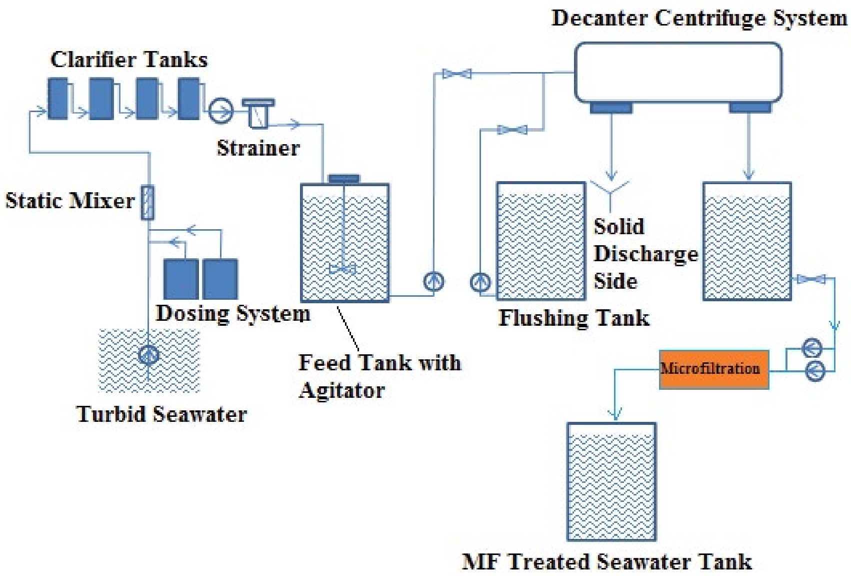

Fig. 2. Flow diagram of the decanter centrifugation unit.

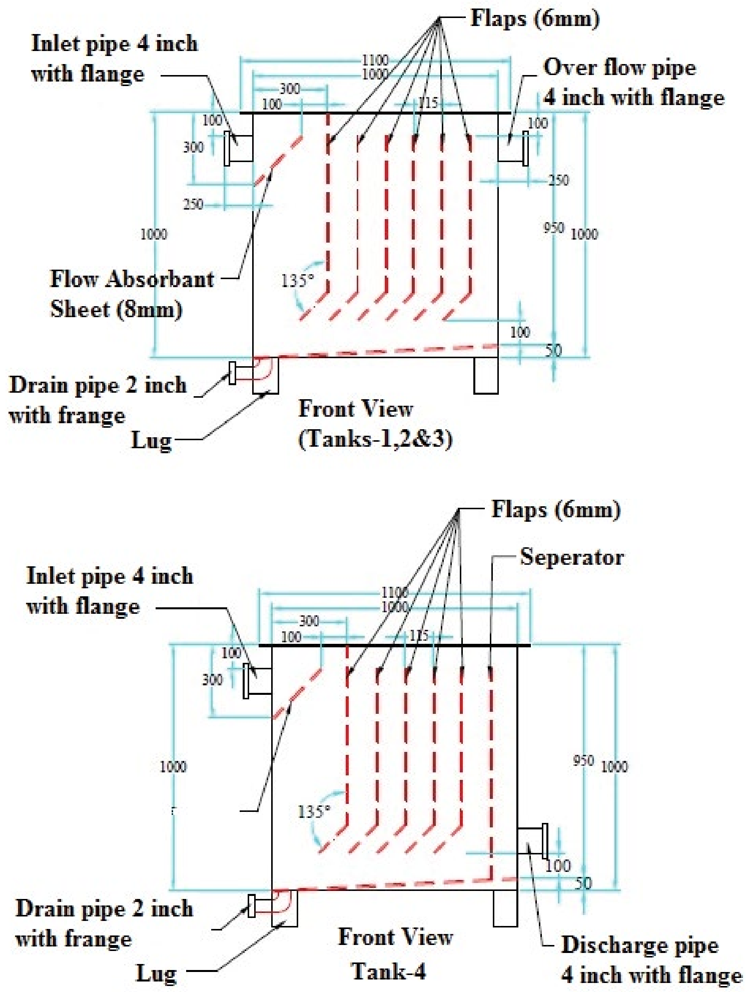

Fig. 3. Front view of the clarifier tanks.

The inlet connection is positioned at 100 mm from the top of the tank, whereas the outlet connection is positioned at 10 mm from the bottom of the tank.

- The fourth tank has 4-in. connections that end with a flange for further connection. This connection is used as an overflow positioned at 100 mm from the top of the tank.

The decanter centrifugation was procured from the International Tunneling Equipment (ITE), Dresden, Germany. The decanter centrifugation feed tank is equipped with an agitator to prevent silt/sand precipitation. One centrifugal pump is then used to pump the turbid seawater feed to the decanter centrifugation system through a centrally arranged inlet tube and is then distributed through several tube openings in the interior side of the decanter bowl. The centrifugal force which develops while the decanter bowl is rotating flings the solids onto the internal walls of the bowl where they form a sediment layer. The solids are delivered through a screw conveyor to the solids compartment and are then supplied through outlet openings in the rotation unit and into the solids chamber in the housing of the decanter. The solids are then supplied through the drain funnel and the spiral conveyer under the section of the decanter and into an outside tank that is positioned below the unit's container. The treated seawater flows into the rear section of the rotation unit where it passes four overflow circular slots to the liquid chamber and directly to either the product tank or passes through a 5 µm-cartridge filter. The rotation unit has a cylindrical shape with a conical end. The cylindrical part features the drain for the treated seawater which is called the liquid compartment. The conical part features ejection openings for discharging the solids/concentrated turbid seawater into the solid chamber of the housing which is called the solid compartment. Automatic flushing of the decanter centrifuge unit is performed using permeate at every plant shutdown through the cleaning/and/or flushing pump. By flushing the remaining seawater along with the removal of accumulated silt and sand inside the unit, scaling and corrosion due to stagnation are minimized and solidification of fine silt and sand is prevented. The decanter system is also equipped with an automated dosing system and an online static mixer for speeding up the chemicals mixing process. The dosing system consists of a tank, dosing pump, agitator, emergency level indicator, and all necessary connections. Finally, the treated seawater will be collected in a tank before feeding into the MF unit.

The schematic presentation of the MF test unit used in the study is presented in Fig. 4. The ceramic membrane-based MF unit with the dead-end operation was supplied by JX Nippon Oil and gas, Chiyoda, and Metawater. The ceramic membrane (Fig. 5) with the dimension of ϕ 180 mm × 1,500 mmL, nominal pore size 0.1 µm, cell inner diameter ϕ 2.5 mm, number of cells 2,000, and total membrane surface area of 25 m^2 was used in the study. The MF unit trials were conducted in batches and there was no direct connection to the decanter centrifuge unit.

2.2. Experimental procedure

The experiment was performed using a decanter centrifuge unit with the operating parameters set as bowl rotation speed of 2,500 rpm, circular slots of 25% closed, the speed difference between bowl and screw of 35 rpm, and seawater feed flow of about 3.5 m^3/h. The performance in this test was monitored for about 11 d of continuous operation and the data was recorded every hour. During each hour, turbidity readings were measured twice for water

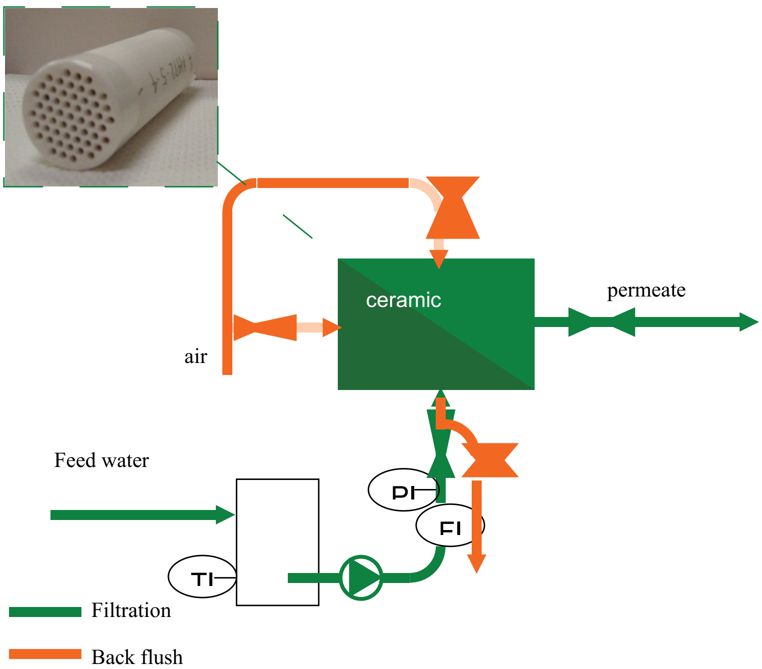

Fig. 4. Flow-sheet of the microfiltration unit.

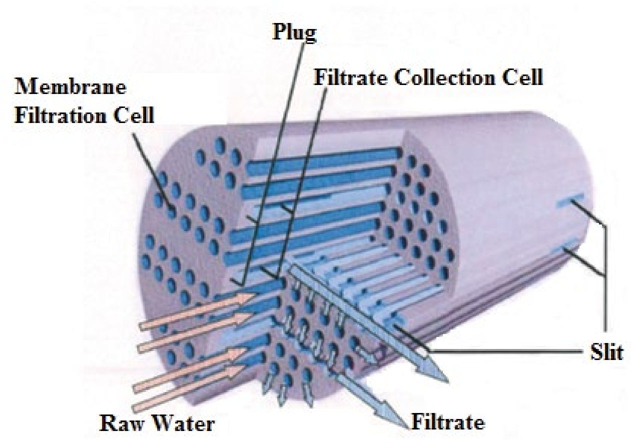

Fig. 5. Cross-sectional view of the ceramic membrane element.

samples collected from seawater intake, seawater after clarifier tanks, and seawater after decanter centrifuge and product of the decanter centrifuge after passing through a 5 µm cartridge filter. During a total actual testing time of 264 h of operation, the decanter unit was stopped a few times due to the accumulation of grease in the decanter bowl and screw motor bearings. The total stoppage time did not exceed 1 h of the total operation time. Because of this, the actual testing period was longer than the actual running time, providing the decanter unit's 99.6% availability. In general, the decanter unit must be shut down to grease the screw, bowl, and gearbox of the decanter centrifuge unit for periods of 15, 30, and 60 min each for 100, 200, and 250 running hours of operation, respectively.

In this study, polyelectrolyte was injected through the dosing line at a rate of 2 ppm (Fig. 3). Polyelectrolyte usually comes in a powder form, and laboratory tests using turbid seawater samples collected from SPDP's intake showed that the best dosing rate was 2 g of polyelectrolyte per one liter of freshwater. Furthermore, a few more tests were also carried out using seawater produced by the decanter centrifuge as a feed to an MF unit as shown in Fig. 3. The MF treated seawater was further tested to obtain SDI measurement values that will be used as an indicator of the suitability of the treated seawater for use as feed to the RO unit. The average water chemistry of the seawater at SPDP site is presented in Table 1. As can be inferred from this Table, the seawater's NTU fluctuated markedly over the experiment's period.

Table 1
Average water chemistry data of the seawater intake at SPDP during the experiment's period

Parameter	Concentration
pH	8.02
TDS, mg/kg	44,808.44
TSS, without washing, mg/L	45.49
TSS, washed with distilled water, mg/L	9.94
Turbidity, NTU	Min.: 5, Max.: 985, Avg.: 20
Chemical oxygen demand (COD), mg/L	86.70
Oil in water, mg/L	1.50
Alkalinity (HCO_3, as $CaCO_3$), mg/L	134.67
Conductivity (EC), mS/cm	61.53
Sodium (Na), mg/L	13,720.54
Calcium (Ca), mg/L	512.68
Magnesium (Mg), mg/L	1,519.66
Chloride (Cl), mg/L	23,500.22
Sulphate (SO_4), mg/L	3,342.70
Nitrate (NO_3), mg/L	3.24
Fluoride (F), mg/L	3.67
Silica (SiO_2), mg/L	1.29
Phosphate (PO_4), mg/L	0.15
Strontium (Sr), mg/L	7.00
Potassium (K), mg/L	388.54
Iodine (I), mg/L	0.19
Barium (Ba), mg/L	<1.0
Ammonia (NH_3), mg/L	<1.0
Zinc (Zn), mg/L	0.03
Copper (Cu), mg/L	0.08
Chromium (Cr), mg/L	<0.1
Iron (Fe), mg/L	0.34
Cadmium (Cd), mg/L	<0.1
Manganese (Mn), mg/L	0.01
Nickel (Ni), mg/L	<0.01
Lead (Pb), mg/L	<0.01
Mercury (Hg), mg/L	<0.01
Aluminum (Al), mg/L	<0.01

TDS: Total dissolved solids; TSS: Total suspended solids.

3. Results and discussion

3.1. Effect of decanter centrifuge treatment on the quality of the turbid seawater

Fig. 6 shows that the fluctuation in seawater turbidity ranged between a minimum of 7 and a maximum of 974 NTU (which cannot be seen in the figure since it is not to scale). The turbidity of the treated product followed a similar trend as the feed with minimum and maximum values of about 5 and 985 NTU.

In fully open mode, a maximum turbidity reduction of 70% was observed with an average of 60%. Fig. 6 also shows that the reduction in turbidity dropped below zero several times since due to the accumulation of silt/sand inside the unit to a level where it started to be re-diluted with the treated seawater. As a result, the operation of the unit had to be stopped on several occasions for cleaning/flushing which was carried out approximately every 18 h of operation and sometimes less, depending on the turbidity of the seawater feed.

3.2. Effect of decanter centrifuge-normal filter treatment on the quality of the turbid seawater

As shown in Fig. 7, the feedwater turbidity fluctuated between a minimum of 20 and a maximum of 233.5 NTU

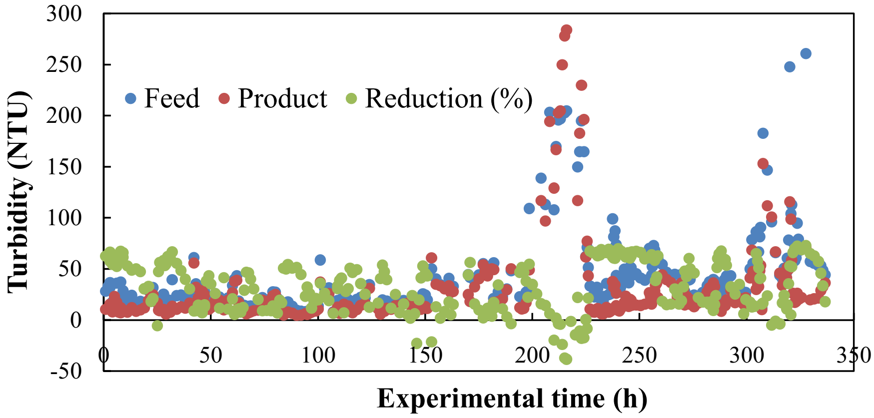

Fig. 6. Variation in feed and product seawater turbidities during the decanter centrifugation treatment (fully open mode) and percentage of reduction in turbidity after treatment.

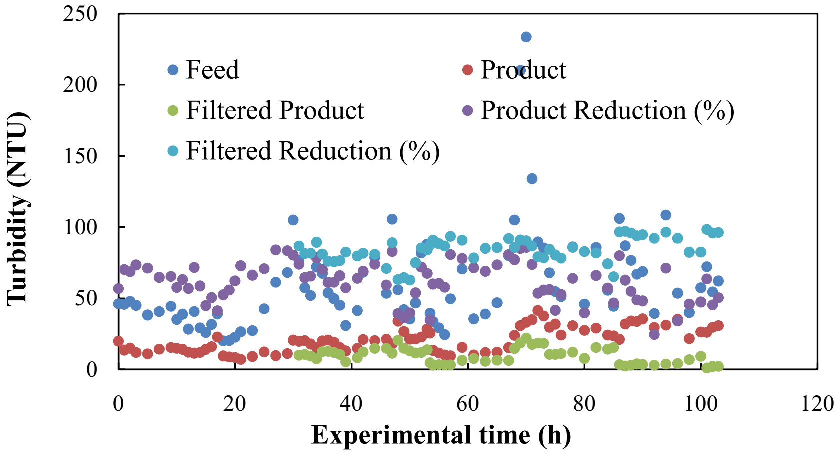

Fig. 7. Variation in seawater turbidity following the introduction of the filter after the decanter centrifuge system (fully open mode) and percentage of reduction in turbidity after treatment.

during the fully open mode operation. The fluctuation in the feed turbidity can be primarily attributed to high winds, low and high tides, and high and low currents. Fig. 7 also shows that the turbidity of the product fluctuated between a minimum of 7 and a maximum of 41.5 NTU. In general, the decanter centrifuge was able to reduce the silt and sand contents of the feed seawater by about 24.6% and 85.7%, respectively. The reduction percentage of the feed turbidity followed a similar trend as the feed, that is, the separation process increased as the feed turbidity increased and vise versa. For example, at 5, 14, 30, 70, and 103 intervals, the turbidity of the feed were 38.25, 29.2, 105, 233.5, and 62.1; while the percentage of reduction in the turbidity levels of the product was 71.2%, 58.7%, 80.3%, 85.7%, and 50.4%, respectively. At 31 h of operation, a 1µm filter was introduced to achieve further reduction in turbidity. At 31, 53, 57, 86, and 101 intervals, the turbidities of the filtered product were 10.1, 14, 3.2, 3.49, and 1.15 NTU, with a total percentage of reduction of 86.8%, 84.1%, 93.55%, 96.7%, and 98.4%, respectively. This clearly indicates the efficiency of the decanter centrifuge coupled with the 1µm filter in removing the sand and silt. The filters were usually changed on a daily basis to overcome the low product flow rates. As can be seen in Fig. 9, at a few intervals, the turbidity of the treated seawater was higher than that of the feed, indicating mixing of the product water with the silt and sand accumulated inside the decanter unit.

3.3. Effect of clarifier tanks treatment on the quality of the turbid seawater

Fig. 8 shows the performance of the four clarifier tanks installed before the decanter unit to stabilize the quality of the feed and to increase the contact time for the coagulation/flocculation process. The seawater feed flow to the tanks was set at 3.5 m^3/h. The data presented in Fig. 8 covered about 220 turbidity readings over 220 h to study the effectiveness of the clarifier tanks treatment in improving the quality of the seawater feed at SPDP. During the monitoring period, Fig. 8 shows that the turbidity of the feed fluctuated from 25.5 to 361 NTU. As can be seen in Fig. 8, the turbidity values of the clarifier tanks product followed a similar trend as the turbidity values of the feed. The increase in the turbidity of the seawater feed resulted

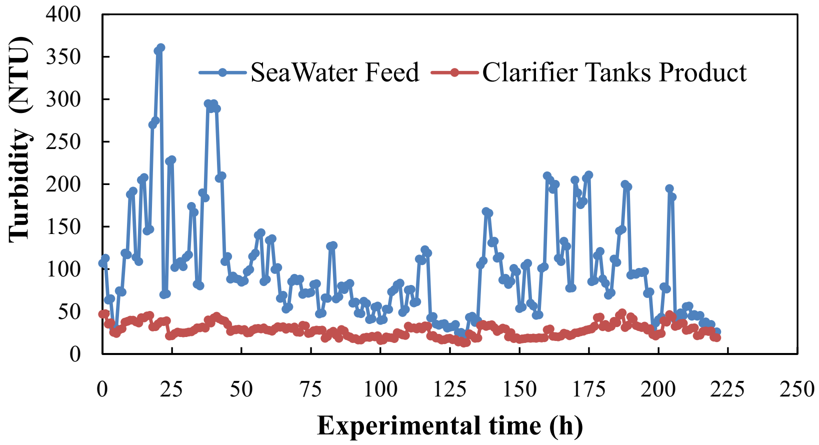

Fig. 8. Turbidities of seawater feed and clarifier tanks product vs. the number of readings.

in an increase in the turbidity of the clarifier tank's product. However, the turbidity values of all of the clarifier tanks' product were below 50 NTU suggesting the effective dosing rate of the polyelectrolyte. This can be seen at readings 1, 8, 11, 21, 40, 163, 188, and 205, the seawater turbidity feed values were 113, 119, 192, 361, 295, 200, 200, 185 NTU, and the product turbidity values were 47.5, 37.4, 38.3, 42.5, 20.4, 31.3, and 43.9 NTU, respectively. At lower feed turbidity values such as readings 2, 5, 22, 59, 130, and 220, the feed turbidities were 63.6, 30, 70, 88, 23, and 25.1 NTU and the product turbidity values were 35.3, 24.2, 38.3, 28.5, 12.9, and 19.9, respectively. Fig. 8, also shows that at higher turbidity feed values, higher reductions in silt and/or sand were achieved. For example, at readings 21, 40, 163, 188, and 205, the reductions of silt and/or sand were 89.4%, 85.6%, 89.9%, 84.35% and 76.2%, respectively. Whereas, at low feed turbidity values, lower reductions in silt and/or sand were achieved. For example, at readings 2, 5, 22, 59, 130, and 220, the reductions of silt and/or sand were 44.5%, 19.3%, 45.3%, 67.6%, 44%, and 20.7%, respectively. This indicated that clarifier tanks coupled with polyelectrolyte dosing are more efficient when the turbidity of the feed exceeds 100 NTU.

Fig. 9 shows the variation in feed, discharge, and product turbidity for the tests carried out using the 50% closed mode. The performance in this test was monitored for 241 h of operation. The rotation speed used during this test was 1800 rpm, which was the maximum speed that can be reached at 50% of closed mode of operation. Fig. 8 indicates that the seawater feed turbidity values fluctuated between minimum and maximum values of about 24 and 216 NTU, respectively. The turbidity of the product at an initial value of about 17 NTU increased to 33 NTU during the next 7 h of operation. The test began immediately after changing the blades without cleaning/flushing and this could explain such a fluctuation in the NTU values after 7 h. After cleaning the unit, the product turbidity value remained at an average of about 7 NTU until 50 h of operation with few peaking exceptions at 57 and 87 h of operation. At 103 h of operation, a 1 μm filter was used causing another 10% to 15% drop in the product turbidity to an average value of less than 1 NTU. The discharge turbidity values ranged from lower to higher than the feed and product, respectively. The low peaks of the reduction values could mean that the unit was stopped, and a cleaning/flushing process took place before the operation continued.

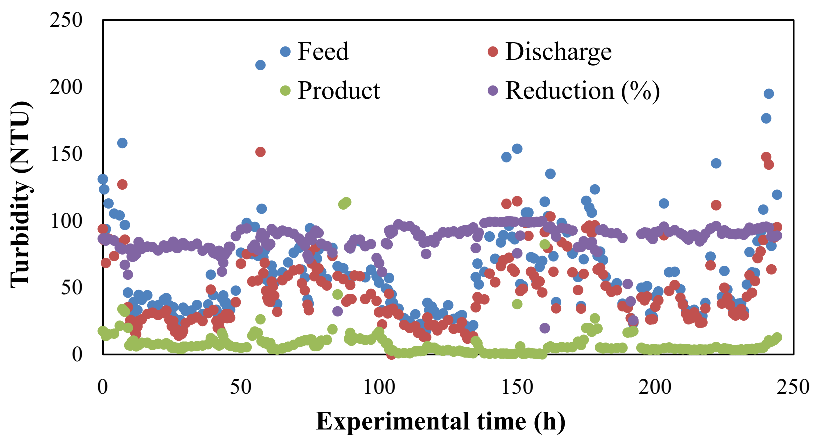

Fig. 9. Variation in feed, product, and discharge seawater turbidities during the decanter centrifugation treatment (50% closed mode) and percentage of reduction in turbidity after treatment.

As shown in Fig. 10, the turbidities of the feed and product before and after the filter were monitored for 200 h of operation using the 50% closed mode operation. During this interval, the feed turbidity values fluctuated between minimum and maximum values of about 4.89 and 74.2 NTU at 107 and 175 h, respectively. However, the turbidity of the feed reached 169 and 364.5 NTU during the 16 and 169 h of operation. The turbidity of the product followed a similar trend as the feed turbidity and fluctuated between minimum and maximum values of 1.4 and 46.4 NTU at 107 and 169 h, respectively. From Fig. 10 it can be inferred that the feed turbidity maintained low values most of the time, and that the turbidity of the product reflected the feed during the testing period. The decanter unit was able to remove 68% to 70% of the silt and sand with a few exceptions (higher removal percentage of 92.5% at 124 h and lower removal percentage of 41.8% at 69 h). This behavior could also be attributed to the particle size of the silt and sand during the treatment period. The turbidity values recorded during the operation period after the 1µm filter were less than 5 NTU. Depending on the turbidity of the feed, a final reduction in the seawater turbidity ranging from 84% to 97% was achieved by the process.

3.4. Effect of decanter centrifuge-microfiltration hybrid treatment on the quality of the turbid seawater

The turbidity of the feed presented in Fig. 11 fluctuated between a minimum of 12.9 and a maximum of 48.5 NTU. Fig. 11 also shows that the turbidity values produced before and after passing through a cartridge filter fluctuated between a minimum of 1.21 and a maximum of 10.7 and 0.5 and 2.76 NTU, respectively. The decanter was able to reduce silt and/or sand from the feed at peak points ranging from 1, 3, 10, 41, 190, and 213 to 90, 91.5, 88.6, 78.4, 90.5, and 89.7, respectively. However, at lower peaks, the decanter centrifuge was able to reduce silt and/or sand at readings 5, 24, 100, 130, 199, and 220 by 92%, 91%, 86%, 84%, 64.7%, and

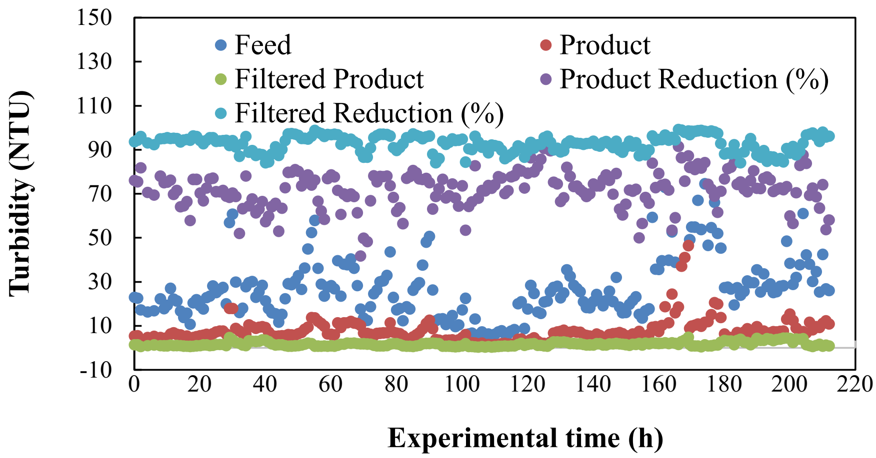

Fig. 10. Variations in seawater turbidity following the introduction of the filter after the decanter centrifuge system (50% closed mode) and percentage of reduction in turbidity after treatment.

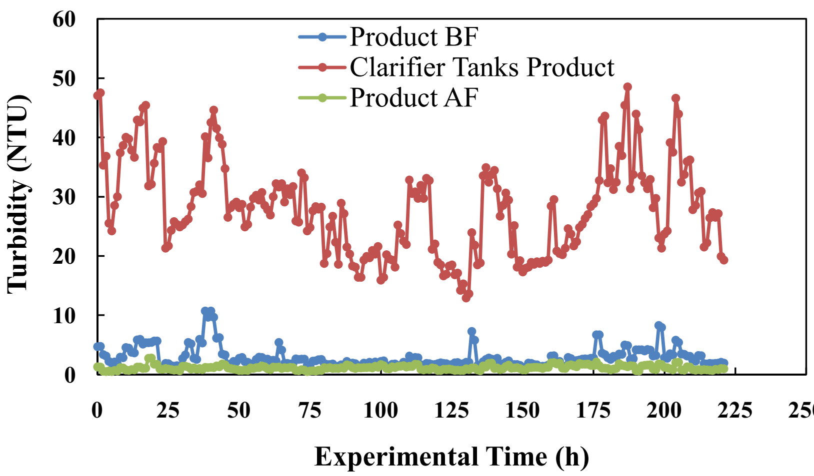

Fig. 11. Variations in seawater turbidity following the introduction of microfiltration after the decanter centrifuge system (before and after the MF treatment).

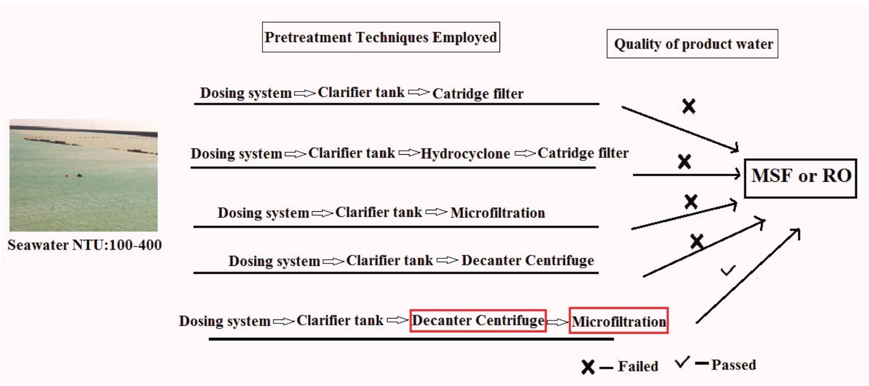

Fig. 12. Schematic presentation highlighting the success of the dosing system-clarifier tank-decanter centrifuge–microfiltration integrated system in providing the desired quality of feed water for both MSF/RO plants compared to other techniques adopted in the study

89.7%, respectively. This shows that in general, the decanter centrifuge unit is capable of reducing 80% or more of the silt and/or sand. The lower reduction rates were due to the start of operation and dosing after each stoppage incident. As for the turbidity values produced after the cartridge filter, it was noted that in most cases where the turbidity values were below 1 NTU, except in three cases, the turbidity values were recorded at readings 18, 19, and 176 were 2.72, 2.76, and 2.08, respectively. This might be due to the size of silt particles passing through the filter at those specific times.

Several silt density index (SDI) tests were conducted using the filtered treated seawater with turbidity values of less than 2 NTU; the best SDI reading value obtained was 6 which is not acceptable for the RO membrane manufacturers. Generally, the RO membrane manufacturers recommend SDI <5. Furthermore, 6 SDI tests were carried out in two batches using the seawater produced by the decanter centrifuge unit as feed to the MF system as described in the experimental tests section. Table 2 shows that the seawater turbidity values obtained using the MF unit were between 0.25 and 0.17 NTU. The quality of the treated seawater obtained using MF as final treatment showed SDI values of less than 3.5 as indicated in Table 2. The results obtained using the MF system as a final treatment for seawater at SPDP intake immediately after the decanter centrifuge unit was promising since the quality was suitable for the safe use of seawater as feed for the membrane and thermal desalination units as well as for power generation equipment.

Table 2
Turbidity and SDI measurement values obtained using MF

Number of SDI tests	Turbidity (NTU)	SDI
1	0.25	3.45
2	0.20	3.35
3	0.20	3.34
4	0.18	3.33
5	0.17	3.325
6	0.17	3.23

SDI measurement values obtained using MF.

Overall, as presented in Fig. 12, different pretreatment approaches were employed and the integration of a decanter centrifuge with MF revealed as the most efficient method in achieving the desired seawater quality for standalone RO or MSF-RO hybrid systems. The currently existing pretreatment methods including decanter centrifuge as a standalone process failed to achieve the desired seawater quality for MSF and/or RO. The integrated process is effective in treating the seawater feed with high NTU (100–400) down to the range of 0.1–0.2 and SDI of >3.5.

4. Conclusions

The quality of the seawater feed at SPDP is currently causing serious damages to the thermal desalination units and to the power generation turbines as the SDI exceeds the measurable range of greater than 5 and hence cannot be utilized for the standalone RO or MSF with turbidity levels exceeding 840 NTU. Therefore, the SPDP site cannot be utilized for hybrid MSF-RO due to the seawater quality since the SDI value of the water feed for RO should be less than 5. The current study evaluated the efficiency of the mechanical decanter centrifuge system followed by an MF unit for the treatment of the high turbid seawater at the SPDP site. Polyelectrolyte dosing along with clarifier tanks placed before the decanter centrifuge unit was very effective in stabilizing the quality of the feed. This study revealed that the decanter centrifuge system is a viable mechanical process for improving the quality of the SPDP's seawater feed. The efficiency of the decanter unit reached 99.6%. Turbidity values obtained immediately after the decanter unit are lower than 5 NTU, however, it was very difficult to obtain SDI measurements below 6. SDI values lower than 3.5 were achieved with further treatment utilizing the MF system. This is an acceptable level that facilitates the safe use of seawater as feed for membrane and thermal desalination units as well as for power generation units. The current pretreatment technology was developed on a prototype level and was tested at the SPDP site. In general, the proposed pretreatment technology can provide a viable solution to freshwater shortage provided that the necessary infrastructure for the establishment of a desalination plant exists. However, this technology is haunted by the quality issues of the seawater feed. Because high-turbidity incidents are common in the GCC countries, it is advised that the proposed pretreatment technology be tested at deltas or in closed Gulf locations.

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