Performance assessment of the stacked microbial desalination cells with internally parallel and series flow configurations

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Performances of five phenol-powered stacked microbial desalination cells (sMDC) with internally parallel and series continuous flow configurations were assessed. The effects of inter-membrane distance (5 and 10 mm) and flow configuration on water desalination were investigated in order to improve the flexibility and footprint of the system. Different sMDC configurations were examined with influent NaCl concentrations of 1–3% at flow rates of 3.5, 7, and 15 \(\text{µL min}^{-1}\). The results of the series flow configurations showed that at NaCl concentration of 1%, reducing the inter-membrane distance (from 10 to 5 mm) of the desalination chamber next to the anode compartment resulted in improved desalination efficiency and specific desalination rate (SDR) while at 3% NaCl concentration, the highest desalination efficiency was achieved with 10 mm inter-membrane distance of both desalination chambers. The results of the parallel flow configurations showed that decreasing the inter-membrane distance leads to distinct effects on desalination efficiency based on the initial NaCl concentration. At NaCl concentration of 1% in contrast to the higher concentrations of 2–3%, an increase in desalination efficiency (36%) was achieved by decreasing the inter-membrane distance. Overall, in parallel flow configurations, the SDR trend was incremental (16–27%). It can be concluded that the different behavior of the sMDC at high and low NaCl concentrations should be taken into consideration in order to optimize the design and operation of these desalination systems.

1. Introduction

The amount of fresh water on earth is limited and more than 97% of the earth's total water supply is saltwater \cite{1}. By 2025, half of the world’s population will be living in water-stressed areas; therefore, desalination of brackish and seawater as an approach to address potable water scarcity problem has attracted a great attention \cite{2,3}. Evaporation, electrodialysis, and reverse osmosis (RO) are the main commercial desalination technologies demanding large amounts of energy either in the forms of electricity or heat. The cost of energy consumption (either traditional or renewable energies) for implementation of these technologies is very high \cite{3}. In a new approach, water can be desalinated in a microbial desalination cell (MDC) using the electricity generated from oxidation of the assimilated carbon substrates by the bacteria in the anode compartment \cite{4}. A typical MDC consists of three chambers including anode, desalination, and cathode.

MDC technology has attracted an increasing attention from the scientific community, and numerous modifications have been made to improve its efficiency. These modifications include the type of membranes \cite{5,6}, reactor shape (tubular or cubic) \cite{7–12}, type of cathode or anode electrodes \cite{13–16}, type of catholyte solution (chemical or biological) \cite{17–19}, system configuration \cite{20} (stacked \cite{3,21–24}, multiple separate MDCs in series \cite{11,25}, multi-stage MDC \cite{26}) and type of carbon source for bacterial growth and maintenance \cite{27,28}.

After the introduction of stacked MDCs (sMDCs) consisting of multiple desalination chambers by Chen et al. \cite{3} which showed an improvement in charge transfer efficiency of MDC systems, various studies were conducted on this system. Kim and Logan \cite{29} desalinated seawater in a series of stacked microbial electro-dialysis cells. A separator coupled sMDC was designed to stabilize the pH imbalance in MDCs between anode and cathode chambers without buffer solution \cite{24}. A bench-scale sMDC packed with ion exchange resins was constructed and operated in the batch mode \cite{30}. The stacked configuration was also used as a means of producing acid and alkali beside seawater desalination \cite{25}. The number of desalination cells was optimized in an enlarged sMDC with equal inter-membrane distances \cite{22}. Chen et al. \cite{31} used a 10-liter bio-cathode sMDC for treatment of

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wastewater and recovery of its nutrients. Dong et al. [32] studied removal of copper using the alkalinity produced in the cathodic chamber of four sMDCs hydraulically connected. Zuo et al. [33] coupled a microfiltration membrane with biocathode sMDC in order to treat wastewater containing organic compounds, suspended solids, and salinity.

Inter-membrane distance could influence desalination performance of sMDCs. Ping and He [12] investigated the effects of inter-membrane distance and hydraulic retention time (HRT) on desalination performance of a conventional three chamber MDC in batch experiments. However, the results might not be generalized to sMDCs. To our knowledge, all previously reported studies were conducted on sMDCs with equal inter-membrane distances while this parameter could have remarkable effects on desalination performance of sMDCs. Therefore, the effect of inter-membrane distance of desalination chambers was investigated in the current study to optimize sMDC performance. Inasmuch as the engineering development of MDC technology is a significant challenge in MDC research [20], the studied sMDCs were operated in series and parallel flow configuration. Choosing the right internal configuration (series or parallel) in each situation would provide a means of lowering the overall cost of desalination systems. Theoretically, the overall desalination performance is affected by flow configuration (series or parallel) and inter-membrane distance in sMDCs. The optimized design of desalination systems according to the initial condition of the saltwater is an important issue in MDC design and immense efforts are underway to identify the most appropriate and important parameters.

Treatment of industrial wastewater and concomitant desalination of salt water can be considered as an attractive advantage of MDCs [34]. Generally, petrochemical and oil/gas refinery complexes are located near the natural salt water resources including seas and oceans. The highly toxic wastewater of these industrial complexes can be used as an available source of carbon and energy for bacterial growth in the anode chamber of the MDCs. Therefore, in the present study, phenol-contaminated water as a synthetic industrial wastewater was used for feeding of anodic bacterial biofilm of a sMDC with two desalination chambers. Desalination performance of the system was examined at three different initial NaCl concentrations (1–3%) and at three different flow rates of 15, 7, and 3.5 μL min⁻¹.

The sMDC was internally operated in continuous series and parallel flow configurations with two different inter-membrane distances (5 and 10 mm) in order to find the most efficient conditions. The effects of salt concentration and hydraulic retention time (HRT) on desalination efficiency and specific desalination rate (SDR) were also determined.

2. Material and methods

2.1. MDC setup

The MDC used in this study was a five chamber reactor. MDC design was based on a cubic-shaped MFC, where the chambers were produced by drilling 3 cm holes in solid blocks of polycarbonate. The five chambers (anode, desalination, concentrate, desalination, and cathode, respectively) were clamped together with plastic gaskets. AMI-7001 anion exchange and CMI-7000 cation exchange membranes (Membranes International, USA) were used between chambers in the order of AMI, CMI, AMI, and CMI starting from the anode chamber. The volumes of the anode and cathode chambers were 14 cm³, and the working volume of anode chamber was 12.5 cm³. The anode was a heat treated (450 °C, 30 min) carbon graphite fiber brush, and the air cathode was carbon cloth (30% wet proofed) with platinum catalyst on the water-facing side (3.5 mg Pt over 7 cm²) and four Polytetrafluoroethylene (PTFE) diffusion layers on the air-facing side [35]. A copper wire was used to connect the electrodes using a 1.0 kΩ resistor.

2.2. Operating conditions

The anode electrode with a stabilized bacterial biofilm was obtained from an operating phenol feeding microbial fuel cell (MFC) which was initially inoculated with activated sludge solution obtained from the industrial wastewater treatment plant of the Research Institute of Petroleum Industry (RIPI). The stabilized bacterial biofilm was capable of using phenol as the sole source of carbon and energy at the optimum concentration of 700 ppm and simultaneously producing bioelectricity [36]. In the current study, the anolyte solution was phenol (700 ppm) in a phosphate buffer solution (20 mM, pH 7.2) containing (per liter in deionized water): 0.31 g NH₄Cl and 0.5 mL vitamin B complex solution. Anodic bacteria were fed with this solution at an optimum flow rate of 100 μL min⁻¹ using a BT100-1L peristaltic pump (LongerPump, China). The optimum concentration of phenol (700 ppm) and its flow rate were chosen based on our previous study with MFC [36]. Cathode chamber was filled with phosphate buffer solution (50 mM, pH 7.2). The desalination chambers were continuously fed with NaCl solution (1–3%) in series and parallel mode at three different flow rates (3.5, 7, and 15 μL min⁻¹) using a BT100-1F multi-channel peristaltic pump (LongerPump, China). The highest examined NaCl concentration of 3% was chosen based on the average salinity of seawater. The lower NaCl concentrations (1 and 2%) are representative of brackish water. Flow rate of the salt water was set at different values to establish HRT values of 4–68 h in the constructed sMDC systems. Effect of inter-membrane distance on desalination performance was investigated by varying the inter-membrane distance of desalination and concentrate chambers. All experiments were carried out in duplicate in the same sMDC at controlled temperature of 25 °C. All analytical measurements were conducted in triplicate. The five sMDC configurations examined in the current study (Fig. 1) were named P1, P2 (for internally parallel flow configuration), S1–S3 (for internally series flow configuration).

2.3. Analysis and calculation

The MDC voltage was measured using GDM-8341 multimeter (GWInstek, China) and data were automatically recorded using GDM-834x software. The conductivity of salt water was measured by a benchtop 4520 conductivity meter (Jenway, UK). The charge transfer efficiency was calculated as the ratio of theoretical amount of coulombs required to remove NaCl to the coulombs obtained as electric current (Eq. 1) [3,12,37]. It is assumed that for removal of one mole of NaCl, one mole of electron is required. Total charge transfer efficiency in parallel configuration was calculated using Eq. (2) assuming the same flow rate in both of the parallel desalination chambers.

\[
\eta = \frac{\Delta C \cdot q \cdot F}{M \cdot I}
\]

\[
\eta_{\text{parallel}} = \frac{\eta_1 + \eta_2}{2}
\]

where F is the Faraday’s constant (96,485 C mol⁻¹), q is the flow rate of the NaCl solution (L s⁻¹), I is the produced current (A), M is the molecular weight of NaCl (58.5 g mol⁻¹), \(\Delta C\) is the difference between influent and effluent NaCl concentrations (g L⁻¹), \(\eta_1\) and \(\eta_2\) are the charge transfer efficiencies of the first and the second parallel desalination chambers.

Desalination efficiency was determined as the percentage of decrease in conductivity of salt solution [12]. The specific desalination rate (SDR) was calculated as the total salt removed from the salt water per day per liquid volume of the desalination chambers [3]. The electric field strength (EFS) was calculated by dividing the MDC voltage by the distance between the anode and the cathode electrodes [3,12].

In order to compare the results of experiments, statistical analysis of the data was performed using the Minitab software (version 17.1.0) with 95% confidence interval.
3. Results and discussion

The stacked MDC system (sMDC) introduced by Chen et al. [3] was studied under fed-batch conditions and it was shown that by increasing the number of desalination chambers a remarkable increase in total desalination rate (TDR) is achieved. In the current study, the performance of a continuous flow sMDC was investigated at two different flow configurations of salt solution into the desalination chambers: parallel and series (Fig. 1).

3.1. Desalination performance of parallel configurations

3.1.1. P1 configuration

As the first step, a sMDC system similar to the one used by Chen et al. [3], with two identical desalination chambers (inter-membrane distances of 5 mm) was examined under continuous internally parallel flow conditions (Fig. 1a) at 1–3 (wt%) NaCl concentrations and flow rates of 3.5, 7, and 15 μL min⁻¹. The distance between the two desalination chambers was set to 10 mm. This configuration is called P1 throughout this study. The results showed that there is some difference in salt removal efficiency between the two desalination chambers which is due to difference between flow rates of salt solution to these chambers as well as water osmosis. Water osmosis under the closed-
circuit condition can extract water from the anode compartment [38]. Water osmosis involves the passage of water molecules from a low concentration to a high concentration solution across a membrane; thereby affecting the desalination efficiency [5]. In P1 configuration, NaCl removal efficiency at an influent salt concentration of 1% increased from 6.11 ± 0.21% (HRT of 4 h) to 22.30 ± 0.08% (HRT of 16 h). The same increasing trend in desalination efficiency was observed at an influent salt concentration of 2% (5.00 ± 0.14% at HRT = 4 h, 18.95 ± 0.16% at HRT = 16 h) and 3% (6.40 ± 0.17% at HRT = 4 h, 12.40 ± 0.22% at HRT = 16 h). Therefore, the results clearly showed that by increasing HRT in this configuration higher desalination efficiency at all examined influent salt concentrations is obtainable due to longer desalination time available at higher HRTs (Fig. 2a) [12].

Increasing influent NaCl concentration from 1 to 3% at an HRT of 4 h led to an increase in desalination efficiency from 6.11 ± 0.21% to 6.4 ± 0.17%. The same increasing trend was observed at an HRT of 8 h (7.74 ± 0.11% at 1% to 8.92 ± 0.02 at 3% NaCl concentration). However, when HRT was 16 h, desalination efficiency decreased from 22.30 ± 0.08% to 12.4 ± 0.22% by increasing influent NaCl concentration from 1 to 3%. This can be attributed to the higher rate of osmosis at the higher salt concentrations.

Values of SDR for P1 configuration is shown in Fig. 3a. According to the results, by increasing influent NaCl concentration from 1 to 3%, SDR values increased at each examined HRT. The same increasing trend was also observed by Ping and He [12] in a conventional MDC system. At 1 and 2% influent salt concentrations, by increasing HRT from 4 to 16 h, a slight decrease in SDR was seen while increasing HRT at NaCl concentration of 3% resulted in a substantial decrease in SDR value (from 23.88 at HRT of 4 h to 8.61 at HRT of 16 h).

3.1.2. P2 configuration

As the next step, inter-membrane distances of the desalination chambers were increased from 5 mm to 10 mm (P2 configuration) in order to increase desalination performance of the sMDC by increasing HRT (Fig. 1b). As indicated in Fig. 2a, NaCl removal in this configuration at 1% influent salt concentration increased from 9.45 ± 0.05% to 16.41 ± 0.24% by increasing HRT from 8 to 32 h. By the same increase in HRT, salt removal efficiency increased from 6.78 ± 0.09% to 22.03 ± 0.22% and from 11.37 ± 0.27% to 18.33 ± 0.33% at influent NaCl concentrations of 2 and 3%, respectively. The results indicated that with a decrease in flow rate of salt water (or equally an increase in HRT) salt removal efficiency increases at all influent salt concentrations when the sMDC system works in the P2 configuration. This effect can be attributed to the longer desalination time [12,25].

In this sMDC configuration, SDR as indicated in Fig. 3a decreased from 4.76 to 1.89 g L⁻¹ day⁻¹ at the lowest examined influent NaCl concentration (1%) when HRT increased from 8 to 32 h. By increasing HRT from 8 to 32 h at higher NaCl concentrations of 2 and 3%, SDR decreased from 5.58 to 4.87 g L⁻¹ day⁻¹ and from 17.19 to 7.40 g L⁻¹ day⁻¹, respectively. As a conclusion, an increase in HRT could lead to a decrease in SDR at every salt concentration.

Salt removal efficiency in the sMDC system working in P2 configuration increases by increasing influent salt concentration from 1 to 3% at all HRT values. This effect may be explained by the lower internal resistance of the system due to higher salt concentration in the...
54.8 ± 1.8 to 50.2 ± 1.9 mV cm

in increasing HRT can also be observed at 2 and 3% NaCl concentrations. desalination chambers [25].

According to Fig. 4a, an increment in HRT from 8 to 32 h when the influent salt concentration is 1% results in a decrease in EFS value from 54.8 ± 1.8 to 50.2 ± 1.9 mV cm

-1. This decreasing trend in EFS with increasing HRT can also be observed at 2 and 3% NaCl concentrations. This is due to the higher efficiency of desalination at higher HRT values [12]. The obtained data also showed that by increasing the concentration of influent NaCl solution, an increase in EFS is achievable at all HRT values (Fig. 4a) obviously because of the lower internal resistance of the sMDC system as a consequence of higher concentration of NaCl in the desalination chambers [12,20].

3.1.3. Effect of inter-membrane distance on the performance of sMDC with parallel flow configuration

Water osmosis, EFS, and HRT are the main parameters affecting the overall desalination efficiency in the MDC systems [12,20]. The inter-membrane distance directly affects all of these parameters. Theoretically, increasing the inter-membrane distance results in an increase in HRT and osmosis rate and at the same time decreases the EFS values [12]. According to the results presented for P1 and P2 configurations, reduction of inter-membrane distance from 10 to 5 mm results in lower salt removal efficiencies except in the case of two sMDC systems: one with an influent NaCl concentration of 2% and HRT of 8 h and another with an influent NaCl concentration of 1% and HRT of 16 h of P1 configuration (Fig. 2a). This can be attributed to the effect of higher EFS values due to the lower inter-membrane distance in P1 configuration which outweighs the effect of higher HRT due to higher inter-membrane distance in the P2 configuration. Therefore, inter-membrane distance shows contradictory effects on desalination efficiency. This conclusion was also made by Ping and He [12]. This effect is more influential on desalination efficiency in situations with low influent salt concentrations and high HRT values. It can be concluded that under the mentioned conditions, decreasing the inter-membrane distance results in higher desalination efficiency.

In order to include the volume of the desalination chamber into desalination performance, SDR was evaluated [12]. An increasing trend in SDR was observed by decreasing the inter-membrane distance from 10 to 5 mm at all examined influent NaCl concentrations and flow rates (Fig. 3a). Ping and He [12] also found that small inter-membrane distances are generally beneficial to SDR in conventional single chamber MDCs. The results also showed that a decrease in the inter-membrane distance from 10 to 5 mm at an influent salt concentration of 3% has less effect on SDR enhancement compared to lower NaCl concentrations of 1 and 2% (67.8% versus 276.7% and 175.2%, respectively). This difference can be attributed to the less improvement in EFS at 3% NaCl in comparison to the lower concentrations of NaCl with a decrease in inter-membrane distance. At both examined inter-membrane distances of 5 and 10 mm, with an increase in NaCl concentration from 1 to 3%, SDR improvement was in the range of 64–400%.

Total charge transfer efficiencies for parallel configurations are presented in Table 1. Most of the acquired data were above 100% suggesting the contribution of other factors such as water osmosis, dialysis or ion exchange to electric current and salt removal [6,38]. In contrary to water osmosis, dialysis involves passage of molecules other than water through the membrane which results in reduced initial osmotic pressure and consequent lower desalination [6]. According to the results, with a decrease in inter-membrane distance, lower total charge transfer efficiencies were obtained. Total charge transfer efficiencies were also higher at 3% rather than 2 and 1% NaCl concentrations, confirming contribution of other factors mentioned earlier on salt removal at higher NaCl concentrations and higher inter-membrane distances [12,20].

3.2. Desalination performance of series configurations

Previously, performance of sMDC systems in series configuration has been studied for an optimized number of desalination chambers [22]. However, in addition to the number of desalination chambers, their inter-membrane distances are also important in the overall desalination performance of the sMDC systems. Therefore, in this section of the current study, a sMDC system first introduced by Chen et al. [3] was used as the starting point for investigation of sMDC operation in series configurations and also to study effects of inter-membrane distance on sMDC performance (Fig. 1c).

3.2.1. S1 configuration

According to the data presented in Fig. 2b, an increase in NaCl removal efficiency from 6.44 ± 0.11% at an influent flow rate of 15 μL min

-1 (HRT = 8 h) to 23.75 ± 0.15% at an influent flow rate of 3.5 μL min

-1 (HRT = 32 h) was seen when the influent NaCl concentration was set to 1%. At influent NaCl concentrations of 2 and 3%, the same increasing trend in desalination efficiency with increasing HRT from 8 to 32 h was observed (6.71 ± 0.07% to 22.54 ± 0.04%, and 7.2 ± 0.12% to 21.35 ± 0.14%, respectively). Therefore, HRT showed a direct influence on desalination efficiency. By increasing NaCl concentration (from 1 to 3%) at an HRT of 8 h, a mild increase in desalination efficiency was seen. Further increase in HRT to 16 h led to no significant changes in desalination efficiency with increasing NaCl concentration from 1 to 3% concentrations. At the longer HRT (32 h), by increasing NaCl concentration, a mild decreasing trend in desalination efficiency was seen which can be attributed to the lower rate of osmosis at lower NaCl concentrations [12].

The SDR values calculated for S1 configuration has been presented in Fig. 3b. It is obvious that at all examined HRTs, the values of SDR have been increased between 170 to 250% by increasing NaCl concentration from 1 to 3%. However, increasing HRT (from 8 to 32 h) at all examined influent NaCl concentrations resulted in a decrease
Table 1. Total charge transfer efficiency of sMDC systems with series and parallel configurations.

<table>
<thead>
<tr>
<th>NaCl concentration (%)</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>102.13 ± 1.74</td>
<td>204.94 ± 2.14</td>
<td>776.64 ± 4.15</td>
</tr>
<tr>
<td>3%</td>
<td>337.77 ± 5.53</td>
<td>71.79 ± 4.93</td>
<td>103.77 ± 5.53</td>
</tr>
<tr>
<td>5%</td>
<td>111.33 ± 1.14</td>
<td>215.57 ± 4.88</td>
<td>67.95 ± 0.77</td>
</tr>
<tr>
<td>7%</td>
<td>66.26 ± 0.59</td>
<td>140.64 ± 0.38</td>
<td>184.39 ± 0.27</td>
</tr>
</tbody>
</table>

3.2.2. S2 configuration

In the following, the inter-membrane distances of the desalination chambers were increased from 5 to 10 mm in order to increase desalination efficiency by increasing HRT. This increase in the inter-membrane distance caused a twofold increase in HRT. This configuration is called S2 throughout this study (Fig. 1d). By increasing the influent NaCl concentration from 1 to 3%, desalination efficiency improved at all influent flow rates from 41 to 328% (Fig. 2b). Also, by increasing HRT from 16 to 64 h, salt removal efficiency increased by 289, 587, and 28.6% at influent NaCl concentrations of 1–3%, respectively. Therefore, HRT in comparison to influent NaCl concentration has a greater effect on desalination efficiency.

Increasing the influent NaCl concentration from 1 to 3% resulted in a 322 to 1180% increase in SDR at HRTs of 16, 32, and 64 h (Fig. 3b). At 3% influent NaCl concentration, an increase in HRT resulted in a decrease in SDR values (from 8.58 g L⁻¹ day⁻¹ at HRT of 16 h to 2.58 g L⁻¹ day⁻¹ at HRT of 64 h) which is common to all examined sMDC systems.

According to Fig. 4b, increasing NaCl concentration from 1 to 3% resulted in 18–20% increase in EFS values at all examined flow rates. However, decreasing HRT from 64 to 16 h caused an increase (2.7–7.9%) in EFS values at all tested salt concentrations. Therefore, it can be concluded that increasing the influent NaCl concentration has a more pronounced effect on EFS than decreasing HRT.

3.2.3. S3 configuration

In order to find the optimized inter-membrane distance in sMDC with series configuration, the inter-membrane distance of the desalination chamber next to the anode compartment was reduced from 10 to 5 mm while the other desalination chamber remained unchanged (10 mm) (Fig. 1e). This configuration was named S3. According to Fig. 2b, with an increase in NaCl concentration, no constant trend was seen in desalination efficiency at each tested HRT. At HRT of 12 h, increase of salt concentration from 1 to 2% and then to 3% resulted in an increase in desalination efficiency from 11.8 ± 0.20 to 16.43 ± 0.08% and then a decrease to 11.57 ± 0.04%. At HRT of 24 h, an increasing trend from 15.85 ± 0.15 to 18.05 ± 0.22% was observed. No significant change in desalination efficiency (about 21%) was seen with an increase in NaCl concentration from 1 to 3% at an HRT of 48 h. On the other hand, 30–82% increase in desalination efficiency was observed at all examined influent NaCl concentrations by increasing HRT from 12 to 48 h.

The SDR values calculated for S3 configuration showed an increase between 193–241% with increasing NaCl concentration at different flow rates while increasing HRT (from 12 to 48 h) has a negative effect (drop by 57–69%) on SDR at all influent NaCl concentrations (Fig. 3b). Therefore, NaCl concentration is more influential than HRT on SDR value.

Increasing NaCl concentration from 1 to 3% at all influent flow rates resulted in 27–40% increase in EFS values while decreasing HRT from 48 to 12 h led to 0.4–5.7% increase in EFS values (Fig. 4b). As a result, increasing NaCl concentration has a greater influence on EFS than decreasing HRT.

3.2.4. Effect of inter-membrane distance on the performance of sMDC with series flow configuration

Comparison of the data obtained from S1 and S2 configurations showed the contradictory effect of inter-membrane distance on desalination efficiency. This behavior is highly dependent on influent NaCl concentration and HRT. At influent NaCl concentration of 1%, increasing the inter-membrane distance from 5 to 10 mm, resulted in 3 to
32% decrease in desalination efficiency despite of 12–14% decrease in EFS values. At influent NaCl concentration of 2%, increasing the inter-membrane distance at flow rates of 7 and 15 μL min⁻¹ resulted in 20 and 44% decrease in desalination efficiency and 1.9 and 16% decrease in EFS values, respectively. However, with an influent flow rate of 3.5 μL min⁻¹ at the same NaCl concentration, a 14% increase in desalination efficiency and a 9.5% decrease in EFS were observed. At the higher NaCl concentration (3%), increasing the inter-membrane distance resulted in 12–1600% increase in desalination efficiency despite of 11 to 18% decrease in EFS values. Therefore, it can be concluded that the effect of inter-membrane distance on desalination efficiency is different at low (1%) and high (3%) influent NaCl concentrations. In other words, increasing the inter-membrane distance has a negative effect on desalination efficiency at low NaCl concentrations and a positive effect at high NaCl concentrations although EFS values always show a decreasing trend (Figs. 2b and 4b).

The SDR values calculated for sMDCs with series flow configurations also show a decreasing trend with an increase in the inter-membrane distance from 5 to 10 mm at all examined influent NaCl concentrations and all tested flow rates (Fig. 3b). Even though a clear relationship between SDR and inter-membrane distance was not found by Ping and He [12] in a conventional MDC, our results with sMDC systems clearly showed a reverse relationship between SDR and inter-membrane distance in all examined sMDCs.

The comparison of results obtained from S3 configuration with the other ones (S2 and S1) showed that at the low NaCl concentration (1%), the S3 configuration has higher desalination efficiency (2–83%) than the S1 configuration. Desalination efficiency of the S3 sMDC was also higher than (9–170%) the sMDC with S2 configuration. Therefore, it can be concluded that the S3 configuration is the most efficient configuration at low NaCl concentration (1%) which can be used instead of S1 and S2 configurations without losing any efficiency and at the same time enhanced SDR values. However, at higher influent NaCl concentration (3%), the S2 configuration was more efficient in desalination than the S1 configuration (12–1600%) and S1 configuration was more efficient than the S3 configuration (14–61%). Therefore, at the NaCl concentration of 3%, the highest desalination efficiency was achieved using the S2 sMDC system.

According to Fig. 3b, the S3 configuration showed an increase of 22–230% and 67–1083% in SDR values over the S1 and S2 configurations, respectively. Therefore, at all examined influent NaCl concentrations and HRT values, using S3 configuration resulted in the highest SDR values.

According to Table 1, the calculated total charge transfer efficiencies of the S2 configuration at high NaCl concentration of 3% was the highest among the other series configurations while the S3 configuration showed the highest total transfer efficiencies at lower NaCl concentrations of 1 and 2% confirming the possibility of choosing optimum configuration at high and low NaCl concentrations.

3.3. Comparison of parallel and series flow configurations in sMDC

Desalination efficiencies of the P1 and S1 configurations were compared at HRTs of 8 h (corresponding to 7 and 15 μL min⁻¹ of P1 and S1 configurations, respectively) and 16 h (corresponding to 3.5 and 7 μL min⁻¹ of P1 and S1 configurations, respectively). The results showed the higher performance (20–70%) of the parallel compared to the series configuration at all examined influent NaCl concentrations. Higher performance can be attributed to the higher EFS and voltage generated in the parallel configuration as a result of higher conductivity of the solution in the desalination chambers [25]. Therefore, desalination efficiency follows the trend of EFS at constant HRT when comparing parallel and series configurations (Fig. 2a, b).

Examining the desalination performance of the P2 configuration in comparison to the S1 configuration at all examined influent NaCl concentrations and HRTs of 16 and 32 h, indicated higher desalination efficiencies (2.3–120%) of the series than the parallel configuration (Fig. 5). The S1 configuration showed a 20–32% increase in EFS values compared to the P2 configuration. However, at the constant HRT of 8 h, the parallel configuration showed higher desalination efficiency (up to 58%) than the S1 configuration at all examined influent NaCl concentrations although the series configuration showed a 15–19% increase in EFS values over the parallel configuration. Inconsistency of desalination efficiency and EFS trend in this case can be attributed to the higher contribution of osmosis, dialysis, or ion exchange in salt removal at the higher inter-membrane distance (10 mm) in the parallel configuration.

4. Conclusions

In this study, two internally parallel and three internally series sMDC systems were examined under continuous flow condition in order to optimize the engineering parameters for future scale-up of this desalination system. In the case of parallel configuration, our results showed that decrease of inter-membrane distance leads to lower salt removal efficiencies and higher SDR values. It is also concluded that osmosis, dialysis or ion exchange have a greater contribution to salt removal at higher inter-membrane distance of 10 mm. The obtained results from sMDC systems with series configurations showed that at low NaCl concentrations, desalination efficiency decreases with an increase in the inter-membrane distance while at high NaCl concentrations an increase in the inter-membrane distance improves the desalination efficiency. In addition, higher SDR values are achievable at short inter-membrane distances. The S3 configuration was shown to be the optimized system with the highest desalination efficiency at low influent NaCl concentration while the S2 is the most suitable configuration for desalination at high influent NaCl concentration. The highest
SDR values were obtained with the S3 configuration. In conclusion, desalination performance of the sMDC system is different at high and low influent salt concentrations and optimization of inter-membrane distances of desalination chambers results in smaller sMDC modules without losing overall performance of desalination systems.

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