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Limitations, improvements and alternatives of the silt density index

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ABSTRACT

Reverse osmosis (RO) membrane systems are widely used in the desalination of water. However, flux decline due to fouling phenomena in RO remains a challenge. To minimize fouling, a reliable index is necessary to predict the fouling potential of the RO feed water. The ASTM introduced the silt density index (SDI) as a standard fouling index to measure the fouling potential due to colloidal and suspended particles. For decades, the SDI is worldwide accepted and applied. There are growing doubts about the predictive value of this parameter. In addition there are several deficiencies observed, affecting the accuracy and reproducibility e.g. no correction factor for temperature, nor for variations in membrane resistance, and no linear correlation with the concentration of colloidal/suspended particles. This paper gives an overview of our work on limitations, improvements and alternatives for the SDI. Firstly, the influence of the applied 0.45 μm test membrane on the SDI will be investigated. Variations in SDI values can be attributed to differences in properties of these membranes. In order to quantify the influence of pressure, temperature and membrane resistance on the SDI a mathematical relation was developed between the SDI and the MFI0.45, assuming cake filtration. In addition, also other fouling mechanisms were incorporated in the model using the well-known blocking laws. Based on a cake filtration fouling mechanism and assuming 100% particle retention, the models were used to normalize the experimental SDI values for temperature, pressure and membrane resistance to the SDI^+. By applying this normalization, the results of SDI tests carried out under different conditions and/or with different membranes can be compared easily as was proven experimentally in the lab and at a seawater desalination plant. Finally, an alternative filtration index will be introduced, the volume-based SDI_v. The SDI_v compares the initial flow rate to the flow rate after filtering a standard volume of feed water using MF membranes with an average pore size of 0.45 μm. Our experimental results show that SDI_v is independent of the membrane resistance. In that way, it eliminates most of the disadvantages of the SDI and has great potential to replace the SDI in the field.

Keywords: Fouling index; Silt density index (SDI); Modified fouling index (MFI)

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1. Introduction

Membrane technology is relatively new, safe, economic and environmentally friendly separation technology for the production of potable water. On the other hand, some problems are present with performance limitation. One of these problems is related to the presence of colloidal and suspended matter in the feed water [1]. These materials tend to foul the membrane surface (covering the surface and blocking pores), plug the spacer in spiral wound elements and plug the hollow fibre bundles.

Fouling of the membrane itself results in an increase in membrane resistance, and as a result higher feed water pressure is required to maintain the capacity of the reverse osmosis (RO)/nanofiltration (NF) plant. Plugging of the spacers initially results in an increase in head loss across the spacer of a spiral wound element, which might damage this element. Subsequently, concentration polarization will increase and an unequal flow distribution will occur. To control the effects of fouling and scaling, (frequent) cleaning might be necessary, which limits the robustness of the technology and generates direct and indirect extra operational cost.

Estimating the fouling tendency of a feed water could be obtained by performing fouling test. Most of the fouling tests are applied under constant pressure. Measuring the flux decline can be done by measuring the accumulation of the permeate volume as a function of time. Several methods were used to describe the fouling potential such as the silt density index (SDI) and the modified fouling index (MFI) [2,3]. The SDI and MFI methods, however, reduce the overall and very complex fouling phenomena to a one number value, on which the interpretation of the fouling potential of the complete feed is based [4].

1.1. Standard ASTM fouling index SDI

The SDI test is an empirical test developed for measuring the rate of fouling of NF or RO membranes. It represents the potential of membranes fouling by finely suspended particles that present in the feed water.

The procedure for measuring SDI is done according to the corresponding ASTM standard. Simultaneously, the flow rate was measured using a flow metre connected to a PC. The times to collect the sample (141 mL) after 15 min of total elapsed flow time were calculated using the filtration collected data. Water temperature was remained constant (±1˚C) throughout the test. The SDI set-up is controlled by software called ViCA, which was built in a LabView environment by Pentair X-Flow. The SDI is calculated according to the following formula:

$$\mathrm{SDI} = \frac{\left(1 - \frac{t_1}{t_2}\right)\%}{t_\mathrm{f}} = \frac{\%P}{t_\mathrm{f}} \qquad (1)$$

where SDI is the silt density index (%/min), t_f is the elapsed filtration time (min), t_1 is the initial time required to obtain the initial sample (s) and t_2 is the time required to obtain an identical second sample after 15 min (or less). If plugging ratio ($\%P$) is exceeding 75%, a shorter period (t_f) has to be taken e.g. 10, 5 or 2 min.

1.2. Modified fouling index (MFI)

The MFI, derived by Schippers and Verdouw [5] from the SDI, was aimed to predict the rate of fouling for RO membranes. For determination of the MFI, the equipment in Fig. 1 was used to measure the flow with interval of 10 s. The total resistance is the sum of the initial membrane resistance and the cake resistance. The total resistance building up is dependent on the particle size through the Carmen–Kozeny equation for specific cake resistance.

$$\frac{t}{V} = \frac{\mu \cdot R_\mathrm{M}}{dP \cdot A_\mathrm{M}} + \frac{\mu \cdot I}{2 \cdot \Delta P \cdot A_\mathrm{M}^2} \cdot V \qquad (2)$$

where, V, filtrated volume (m^3); t, time (s); A_M, membrane area (m^2); dP, applied pressure (Pa) , water viscosity (Pa s); R_M, clean membrane resistant (m^{-1}); I, fouling potential (m^{-2}).

At constant pressure and membrane surface area, the MFI is defined as:

$$\mathrm{MFI} = \frac{\mu \cdot I}{2 \cdot dP \cdot A_\mathrm{M}^2} \qquad (3)$$

1.3. Needs for a reliable fouling index

The SDI test is a simple test to do and thus does not need professionals. This test has some disadvantages which make it an unreliable test. The SDI test itself has some drawbacks: no linear relationship exists between the SDI and the colloidal concentration in the water. Besides that, the SDI is not based on any filtration model. The SDI is not corrected for temperature; it is not measured in situ and is not a continuous test. Consequently, there is growing doubt about the value of the SDI test as a predictive tool for membrane fouling [5–7].

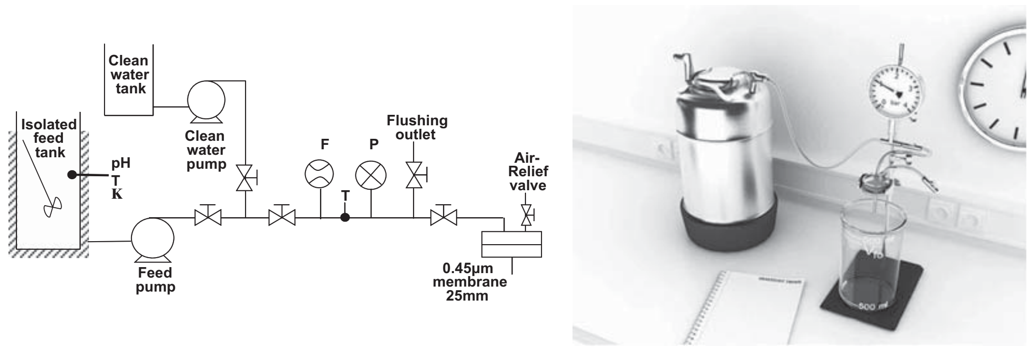

Fig. 1. Flowsheet of the SDI set-up. Feed tank and clean water tank are shown. pH, Temperature (T) and conductivity (K) are measured in the feed tank as well as in the feed line. Pressure (P), flow rate (F) and temperature (T) are measured in the feed line. Valves are controlled using ViCA software.

On the other hand, the MFI is based only on the cake filtration mechanism and is dependent on particle size through the Carman–Kozeny equation for specific cake resistance [8]. Thus, in general, smaller particles present in the cake result in higher MFI values. By assuming cake filtration is the dominant mechanism in particulate fouling, the MFI can be used as a basis for modelling flux decline in membrane systems. However, fouling rates predicted from the MFI as measured for RO feed water were far too low. It was therefore hypothesized that smaller colloidal particles were responsible for the observed flux decline rates in RO [9].

Both fouling indices SDI and MFI are affected by the variation in the properties of the test membranes available in the market. Finally, an RO is operated with cross-flow system and has spacers between the membranes, whereas SDI and MFI are dead-end filtration experiments. Despite all these disadvantages, SDI and MFI currently are the tools to simulate and predict the fouling in the RO [10]. In many cases, SDI and MFI could not provide an accurate prediction of the rate and the extent of RO membrane fouling. This leads to the needs for other approaches for better estimation of membrane fouling potential [3,11].

2. Mathematical bridge between SDI and MFI

2.1. Mathematical approach

The needs for a reliable fouling index are growing with the large growth in the desalination market. The SDI often used worldwide, even with the above mentioned and known drawbacks, is an unreliable index. MFI can be corrected for testing parameters. Effectively, the mathematical bridge between SDI and MFI presented here can be used to study the effect of testing parameters on SDI through MFI.

Starting with the MFI definition, Eq. (2) can be written as [12]:

$$t(V) = \frac{\mu \cdot R_{\mathrm{M}}}{dP \cdot A_{\mathrm{M}}} \cdot V + \frac{\mu \cdot I}{2 \cdot dP \cdot A_{\mathrm{M}}^2} V^2 \tag{4}$$

or

$$t(V) = \frac{\mu \cdot R_{\mathrm{M}}}{dP \cdot A_{\mathrm{M}}} V + \mathrm{MFI} \cdot V^2 \tag{5}$$

$V(t)$ can be calculated using Eqs. (4) or (5):

$$V(t) = \frac{-\mu \cdot R_{\mathrm{M}} + \sqrt{\mu^2 \cdot R_{\mathrm{M}}^2 + 2 \cdot I \cdot dP \cdot t}}{I \cdot \mu} \cdot A_{\mathrm{M}} \tag{6}$$

or

$$V(t) = \frac{1}{2} \frac{-\mu \cdot R_{\mathrm{M}} + \sqrt{\mu^2 \cdot R_{\mathrm{M}}^2 + 4\mathrm{MFI} \cdot dP^2 \cdot A_{\mathrm{M}}^2 \cdot t}}{\mathrm{MFI} \cdot dP \cdot A_{\mathrm{M}}} \tag{7}$$

2.2. Calculating SDI

In Eq. (1), the times t_1 and t_2 to collect V_1 and V_2 need to be determined to calculate the SDI. This can be done using the mathematical approach described below. By assuming a cake filtration mechanism and 100% particle rejection, the SDI can be calculated using MFI definition. The reference testing parameters were set as follows: T 20°C, dP 207 kPa, A_{M} $13.4 \times 10^{-4}\,\mathrm{m}^2$ and R_{M} $1.29 \times 10^{10}\,\mathrm{m}^{-1}$. For a measured MFI value, the initial time t_1 to collect the first sample V_1 can be calculated with Eq. (5). In 15 min, a volume V_{15} will be filtered through the membrane. V_{15} can be estimated with Eq. (7) for t equals 15 min. By the end of the filtration experiment, a total filtered volume

V_{total} ($V_{15}+V_2$) will have been collected. The total filtration time t_{total} for filtering V_{total} can be estimated using Eq. (7). Then, the required time t_2 to collect the second volume V_2 after 15 min can be calculated as: $t_2=t_{total}-15$ min. Finally, t_1 and t_2 were used in Eq. (1) to determine the SDI. Similarly, the fouling potential I can be used to estimate SDI using the equations. Finally, the SDI can be directly calculated as a function of MFI with the following formula:

$$\mathrm{SDI}=\frac{20}{3}\frac{V_2^2\cdot \mathrm{MFI}\cdot dP\cdot A_\mathrm{M}+V_2\cdot\sqrt{\mu^2\cdot R_\mathrm{M}^2+4\cdot t_{15}\cdot \mathrm{MFI}\cdot dP^2\cdot A_\mathrm{M}^2}-\mu\cdot R_\mathrm{M}\cdot V_1-\mathrm{MFI}\cdot V_1^2\cdot dP\cdot A_\mathrm{M}}{V_2(V_2\cdot \mathrm{MFI}\cdot dP\cdot A_\mathrm{M}+\sqrt{\mu^2\cdot R_\mathrm{M}^2+4\cdot t_{15}\cdot \mathrm{MFI}\cdot dP^2\cdot A_\mathrm{M}^2})}\quad (8)$$

where MFI, measured MFI (L/m^6); V_1, volume of the first sample (m^3); V_2, volume of the second sample (m^3); A_M, membrane area (m^2); t_{15}, elapsed filtration time 15 min (900 s); dP, applied pressure (Pa); μ, water viscosity (Pa s).

Clearly, the model represented in Eq. (8) has the capability to predict the SDI value as function of MFI and the testing parameters assuming cake filtration and particle rejection 100%.

3. Results and discussion

3.1. Influence of used membranes

Eight types of membranes were chosen for this work, including the ASTM standard membrane material (Table 1).

α-Alumina hydrophilic particles (AKP-15, Sumitomo Chemical, Tokyo, Japan) were used as model feed, having a core particle size of 0.6 μm and an isoelectric point (IEP) at pH 9 [13]. The AKP-15 is quite monodisperse as revealed by the particle size distribution curve. The feed solution was prepared by dispersing 4 ppm AKP-15 in demineralized water, purified by ultra pure system from Millipore (Synergy SYNS). The solution was well mixed using a mechanical mixer in the feed tank [14].

Fig. 2 gives the SDI values as determined for membranes M1–M8. When the back side of M1 is directed towards the feed, a 0.3 higher SDI value is measured compared to the situation where the top side is facing the feed. Membrane M5 shows the lowest SDI value (2.0 ± 0.23), while membrane M8 results in the highest SDI value (4.6 ± 0.24). Membrane M2 shows the highest variation in the SDI value: 3.8 ± 0.5. The variation in the SDI results of M2 can be explained by the necessary pre-wetting with ethanol due to the membrane's hydrophobicity. During the filtration step, the feed water flushes the ethanol out of the pores and part of the membrane become dry and inactive to water transport, which lowers the flow rate and results in an increase of the SDI value. The dried areas in M2 were frequently observed when the holder was opened directly after the SDI test. Membranes M1_T, M1_B, M3, M4 and M6 show less variation in the SDI values (between 0.21 and 0.25).

3.2. SDI/MFI mathematical modelling

The results of this work will be presented in several sections. The SDI/MFI mathematical relation will be explained and verified. The mathematically derived SDI/MFI relation is working properly if the dominated fouling mechanisms are pure cake filtration. For that reason, the difference between pore blocking and cake filtration will be also explained and examined. The influence of testing parameters such as membrane area, feed temperature and applied pressure is also studied. Finally, the equivalent MFI values for $\mathrm{SDI}_{15}=3$ will be theoretically calculated.

3.2.1. The SDI and MFI relation

In Eq. (8), the mathematical bridge between SDI and MFI was built as a function of the testing parameters. In order to illustrate the SDI/MFI relation, reference testing parameters were assumed: membrane area (A_M) $13\times10^{-4}\,\mathrm{m}^2$, feed temperature 20°C and applied pressure (dP) 207 kPa. The relation SDI/MFI is plotted in Fig. 3 for various membrane resistances: 0.25, 0.5, 1, 2, 4 and $8\times10^{10}\,\mathrm{m}^{-1}$. Increasing the assumed MFI values leads to an exponential increase in the calculated SDI value. Furthermore, the SDI/MFI relation is influenced by the membrane resistance.

Table 1
Microfiltration membranes used in this work. Pore size as given by manufacturer

Code	Material	Nominal pore size (μm)	R_M (10^{10} m^{-1})
M1	PVDF	0.45	0.83
M2	PTFE	0.45	0.41
M3	Acrylic polymer	0.45	0.66
M4	Nitro cellulose[a]	0.45	0.64
M5	Nylon6,6	0.45	2.65
M6	Cellulose acetate[a]	0.45	0.74[0]
M7	Cellulose acetate[a]	0.45	0.85
M8	Polycarbonate	0.45	0.39

[a]ASTM standard membrane material.

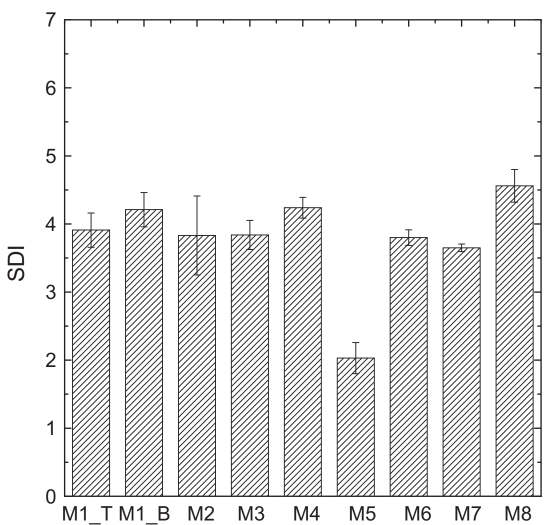

Fig. 2. SDI results using a 4 ppm AKP-15 model feed for the different membranes.

3.2.2. The influence of particle concentration on SDI

MFI has a linear relation with particles concentration as were proved by Schippers and Verdouw [5]. Moreover, SDI has non-linear relation with the particles concentration. Fig. 4 shows the results of nine SDI tests carried out at constant temperature 21.5℃ and constant pressure (207 kPa) for three particle concentrations AKP-15: 2, 4 and 8 ppm. Three SDI tests for each concentration were carried out using the cellulose acetate membrane (M6) with a diameter of 25 mm. The fouling mechanisms were verified as a cake filtration.

In Fig. 4, the experimental SDI results show a good agreement with the theoretical prediction of SDI using model Eq. (8). Both, experimental and theoretical SDI results verify the non-linear relation between SDI and the particles concentration. The slight deviation between the experimental and the theoretical SDI results can be explained as follows:

- Due to the particle size distribution and the pore size distribution, the particle rejection is not 100%. Small particles can pass through big pores.
- The fouling mechanism is not pure cake filtration. The experiment starts with pore blocking in the beginning of the filtration.

3.2.3. The influence of the membrane resistance on SDI

To demonstrate experimentally the influence of the membrane resistance on SDI, different membranes material and manufactures with different membrane resistance were used. The feed solution of 4 ppm α-Alumina particles (AKP-15) was prepared in a big feed tank to remain a constant feed quality. SDI tests were carried at room temperature 21℃. The applied pressure remained constant 207 kPa. SDI results were plotted vs. the membrane resistance in Fig. 5. Besides that, the fouling potential I was calculated for each experiment and the cake filtration was verified. Assuming 100% particle rejection, the model 8 was used to estimate the theoretical SDI value for each experiment. The theoretical SDI values for various membrane resistances were estimated and plotted in Fig. 5.

Clearly, Fig. 5 shows the influence of the membrane resistance (R_M) on SDI. Both theoretical and experimental results show that the SDI decreases with increasing membrane resistance (R_M). In other words, an increase in membrane resistance from $0.5 \times 10^{10}\,m^{-1}$ to $3.5 \times 10^{10}\,m^{-1}$ leads to a decrease in SDI from 4.5 to 2 for the same water quality.

This large influence on the SDI by the membrane resistance can be explained as follows. For a constant particles concentration, the membrane with high resistance has low permeability. Consequently, the amount of particles that are carried to the surface of

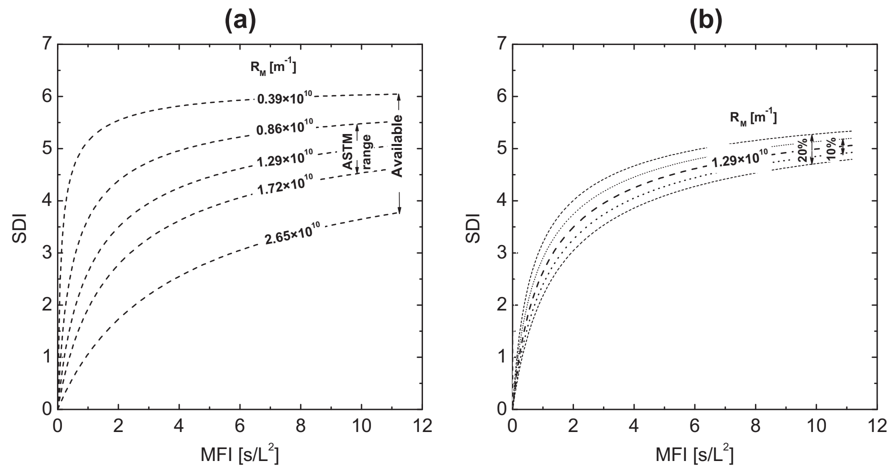

Fig. 3. The mathematical relation between SDI and MFI0.45 as a function of the membrane resistance. (a): ASTM range: 0.86×10^{10} to $1.72 \times 10^{10}\,m^{-1}$. Range of what is available in the market: 0.39×10^{10} to 2.65×10^{10} m^{-1}. (b) Suggested allowable range: ±10 and ±20% of R_{M0} 1.29×10^{10} m^{-1}. Reference parameters assumed: a membrane area (A_M) of $13.8 \times 10^{-4}\,m^2$, a temperature of 20°C and a pressure difference (dP) of 207 kPa.

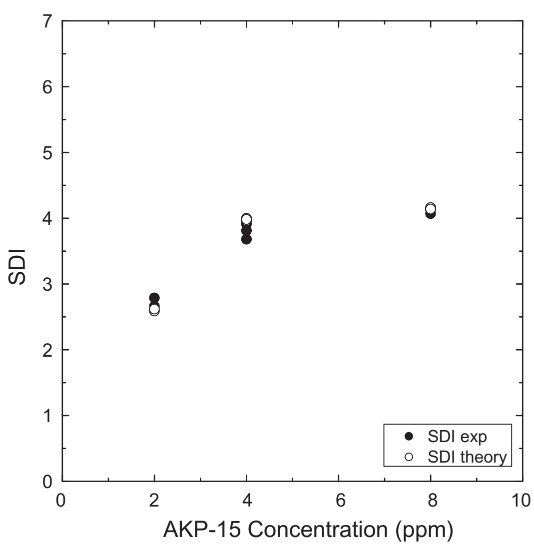

Fig. 4. Theoretical and experimental SDI results for different particle concentrations (2, 4 and 8 ppm). Feed solutions contained α-Alumina particles (AKP-15) with 0.6 μm size. The filtration experiments were carried out using cellulose acetate membranes M6.

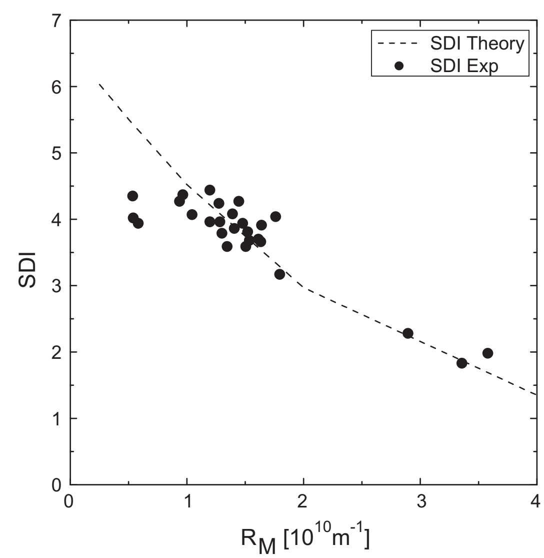

Fig. 5. SDI experimental and theoretical results for different membrane resistance materials and manufactures. The experiments carried out using particles concentration 4 ppm of AKP-15 under pressure 207 kPa.

the membrane with high membrane resistance will be less comparing to that for a membrane with a low membrane resistance. According to the ASTM standard, the SDI is defined as the plugging rate per minute. Consequently, for high membrane resistance, the plugging rate will be slower and SDI will be lower.

The membrane resistance (R_M) can be described as a lump sum of membrane properties such as pore size, porosity, tortuosity and membrane thickness. These membrane properties varied for membrane material and manufacturers, explaining the variation in the membrane resistances.

The deviation between the theoretical and experimental results of SDI in Fig. 5 can be due to small particles passing through the membrane with large pores. Besides that, the chance to start with pore blocking for longer time is high for the membrane with low resistance.

3.2.4. Normalization and sensitivity study of SDI

The standard ASTM SDI test does not contain any correction for testing parameters such as membrane resistance (R_M), membrane area (A_M), feed temperature (T) and applied pressure (dP). The mathematical relation between SDI and MFI in model 8 gives for the first time the opportunity to correct SDI. The membrane area (A_M) has no influence on SDI as far as the sample volumes are adjusted in direct proportion with the membrane area (A_M). Normalizing the SDI needs defined reference values for the testing parameters. In this study, the following reference parameters were suggested:

- Membrane resistance (R_M) $1.29 \times 10^{10}\,m^{-1}$.
- Feed temperature (T) 20°C.
- Applied pressure (dP) 207 kPa.

Now, the SDI can be corrected for the effects of the membrane resistance, temperature and applied pressure using Eq. (8) and the defined reference testing parameters.

Based on a cake filtration fouling mechanism and assuming 100% particle retention, the models were used to normalize the experimental SDI values for temperature, pressure and membrane resistance to the SDI^+ [15]. By applying this normalization, the results of SDI tests carried out under different conditions and/or with different membranes can be compared easily (Fig. 6), as was proven experimentally in the lab and at a seawater desalination plant.

3.3. Alternatives for SDI (SDI_v)

A new volume-based SDI (SDI_v) will be defined. The SDI_v will be compared to the standard SDI and SDI^+ results.

3.3.1. Definition of the volume-based SDI_v

In the SDI test, the time between the two measurements t_f is fixed (5, 10 or 15 min) and the total volume that is filtered in that time depends on the flow rate. Thus, any effect that increases the flow through the membrane will increase the fouling load of the membrane and consequently the measured SDI will be higher. This explains our observation that the SDI increases with increasing temperature (decreasing viscosity implies increased flow), increasing pressure and decreasing membrane resistance [16]. To assure the same fouling load is provided to all the membranes under any testing condition, it is much more logical that the second sample should be collected after a fixed filtrated volume V_{fO} instead of fixed time t_f. In that way, the fouling load will be the same for all SDI determinations. Consequently, the volume-based SDI test will overcome the effects of the testing condition parameters and will decrease the effect of the membrane resistance.

Definition 1

To determine the SDI_v (%/m), the volume-based plugging ratio per specific unit volume (m^3/m^2) of a membrane filter with pores of 0.45 µm and diameter 47 mm at 30 psi (207 kPa) is measured. The measurement is done as follows:

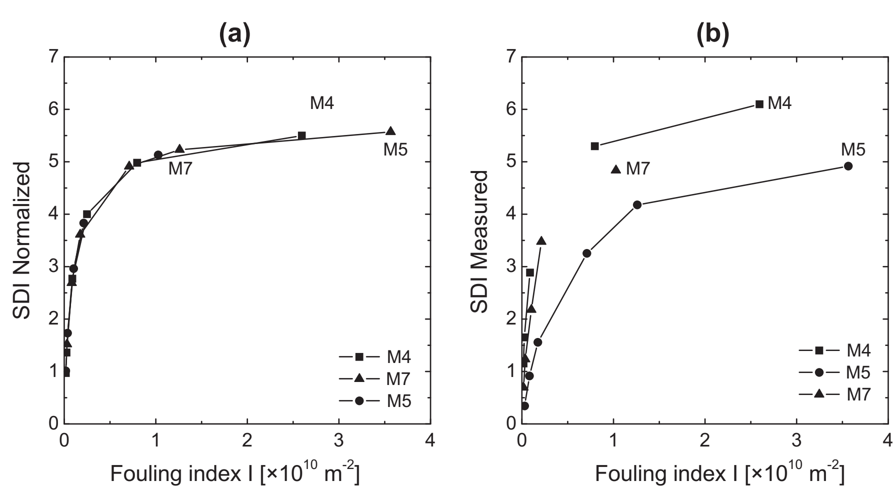

Fig. 6. (a) Measured SDI values (b) SDI normalized for membrane resistance and testing condition parameters $T = 10$°C and $K = 53{,}600\,\mu S/cm$ (SDI^+).

(a) The time t_1 is defined as the time required to filter the first V_1 500 mL.
(b) After a standard volume, V_{fO} is filtered since from the start of this measurement and t_2 is defined as the time required to filter another V_2 500 mL.
(c) The index is calculated using the following formula.

$$\mathrm{SDI\_v} = \frac{100\%}{\frac{V_{fO}}{A_{MO}}}\left(1 - \frac{t_1}{t_2}\right) = \frac{\%P\_v}{\frac{V_{fO}}{A_{MO}}} \tag{9}$$

where t_1 [s] is the time to collect the first sample V_1, t_2 (s) is the time to collect the second sample V_2 after filtrating the standard volume V_{fO}, A_{MO} is the reference membrane area (m^2) and $\%P\_v$ is the volume-based plugging ratio [%].

Definition 2

SDI_v (%m) also can be defined as the plugging ratio after a fixed filtrated volume V_{fO} divided by 15 of a membrane filter with pores of 0.45 μm and diameter 47 mm at 30 psi (207 kPa), where 15 is a dimensionless number to scale SDI_v down to the standard (time-based) SDI values between 0 and 6.66.

$$\mathrm{SDI\_v} = \frac{100\%}{15}\left(1 - \frac{t_1}{t_2}\right) = \frac{\%P\_v}{15} \tag{10}$$

where t_1 [s] is the time to collect the first sample V_1, t_2 [s] is the time to collect the second sample V_2 after filtering the standard volume V_{fO}. Both definitions can be used as the new fouling index. The volume of the first sample V_1 (500 mL), the second sample V_2 (500 mL) and the standard volume V_{fO} should be adjusted in direct proportion to the membrane area. In this study, mainly definition 1 is used unless otherwise mentioned.

3.3.2. *Experimental validation*

The standard SDI and MFI0.45 indices were measured in the Evides RO/UF desalination plant in Jacobahaven, the Netherlands [17]. UF feed was diluted with RO permeate with different dilution ratios to investigate the influence of the foulant concentration on the SDI: 50, 100, 200, 300 and 500 mL of UF feed were diluted in 25 L of RO feed. Three different membranes with different membrane resistances (M4, M5 and M7) were used to carry out the SDI tests.

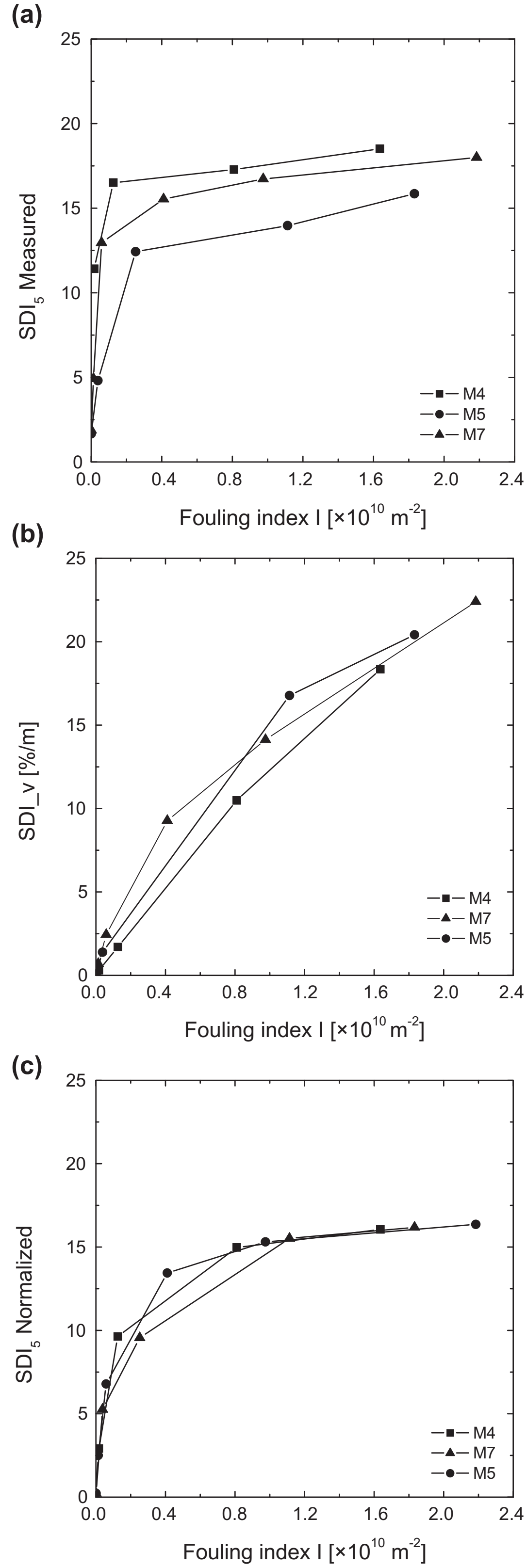

Fig. 7. (a) Standard time-based SDI for 5 min elapsed filtration time, (b) SDI_v values and (c) time-based SDI normalized for the membrane resistance and the testing condition parameters (SDI$^+$).

Table 1 shows the average membrane resistances of these membranes. SDI results were normalized for membrane resistance and temperature (SDI^+).

The filtration data (V vs. t) that were used to calculate the (time-based) SDI can also be used to calculate the SDI_v. Filtration data for the time-based SDI were limited to a total filtration time of 20 min. Based on SDI_v definition 1, an accumulated filtrated volume V_{fO} of 3.65 L was suggested for the 25 mm diameter cell. In case of a high membrane resistance (M5), V_{fO} would need more than 20 min collection time. In order to compare the three membranes with the available data, a standard V_{fO} of 1.25 L instead of 3.65 L was assumed. To obtain a comparable fouling load for the time-based SDI and SDI_v, t_f was decreased to 5 min and the SDI_5 was calculated. The time-based SDI_5, normalized SDI^+ and SDI_ v results were plotted vs. the fouling potential index I as shown in Fig. 7(a)–(c).

In Fig. 7(a) membrane M4 with the lowest membrane resistance shows in the highest SDI at a certain fouling load. Contrarily, M5 with the highest membrane resistance reveals the lowest SDI. SDI_v results based on V_{fO}=1.25 l in Fig. 7(b) show a more linear relationship with the fouling index I. Besides that, the curves of the three membranes are closer to each other. Thus, SDI_v is less sensitive for differences in the membrane resistance compared to the time-based SDI. The standard SDI results were normalized to SDI^+ for the membrane resistance and temperature in Fig. 7(c). The curves of the three membranes are almost identical, especially at higher fouling indexes. An ideal fouling index should not be affected by differences in the membrane resistance and should have a linear relationship with the particle concentration. The membrane resistance affects SDI_v, while SDI^+ has no linear relation with the particle concentration.

The fouling index SDI_v can be calculated through the SDI_v/MFI0.45 relation following steps analogue to those in Section 2 which results in Eq. (11).

$$\mathrm{SDI\_v} = \frac{100}{\frac{V_{fO}}{A_M}}\left(1 - \frac{\frac{\mu \cdot R_M \cdot V_C}{dP \cdot A_M} + \mathrm{MFI} \cdot V_C^2}{\frac{\mu \cdot R_M \cdot (V_{fO} + V_C)}{dP \cdot A_M} + \mathrm{MFI} \cdot (V_{fO} + V_C)^2 - \frac{\mu \cdot R_M \cdot V_{fO}}{dP \cdot A_M} - \mathrm{MFI} \cdot V_{fO}^2}\right) \quad (11)$$

where, V_C is the sample volume $V_C = V_1 = V_2$ and MFI is the modified fouling index. Another option is to determine SDI_v by measuring the fouling potential index I:

$$\mathrm{SDI\_v} = \frac{200 \cdot A_M \cdot I}{2 \cdot A_M \cdot R_M + 2 \cdot I \cdot V_f + V_C \cdot I} \quad (12)$$

4. Conclusions

Several disadvantages were reported, which makes SDI unreliable fouling test. A mathematical relationship between SDI and MF was built in this study. The mathematical relation SDI/MFI can be used to study the effect of testing parameters on SDI such as membrane resistance (R_M), membrane area (A_M), feed temperature (T) and applied pressure (dP).

The membrane resistance has a great influence on SDI. An increasing membrane resistance leads to a dramatic decrease in SDI. ASTM defined limits for the used membrane resistance (R_M) between 0.39×10^{10} and $2.65 \times 10^{10}\,\mathrm{m}^{-1}$.

SDI can be normalized to SDI^+ for T, dP and R_M assuming cake filtration and 100% particle retention.

A new fouling index, SDI_v, is the second fouling index developed at the University of Twente, 30 years after the MFI0.45. The SDI_v compares the initial flow rate to the flow rate after filtering a standard volume V_{fO} using MF membranes with an average pore size of 0.45 μm. SDI_v has a better linear relationship to the particle concentration compared to the standard SDI.

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