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Silt Density Index and Modified Fouling Index relation, and effect of pressure, temperature and membrane resistance

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ABSTRACT

Particulate matter present in feed water of reverse osmosis and nanofiltration membrane elements tends to deposit on the membrane surface and spacers. This type of fouling results in permeate flux decline, loss of product quality and membrane damage. To characterize the fouling potential of RO feed water the Silt Density Index (SDI) and the Modified Fouling Index (MFI0.45) are commonly applied. SDI is applied worldwide for many years on a routine basis by operators since it is a simple and cheap test.
Unfortunately, the SDI has several deficiencies e.g. it is not based on any filtration mechanism, has no linear relation with particulate matter and is not corrected for temperature, pressure and membrane resistance. This might explain the frequently reported erratic results obtained in practice, e.g. water treated with ultrafiltration showed in several cases high SDI values, which could not be attributed to failures of the UF membrane elements or systems. To overcome these deficiencies the MFI0.45 has been developed. This test is based on the occurrence of cake filtration during a substantial part of the test, has a linear relation with particulate matter content, and is corrected for pressure and temperature. However the manual procedure of measuring an MFI0.45 is somewhat more complicated and for this reason less suitable for application on a routine basis in practice.
Fully automated equipment, measuring SDI and MFI0.45 at the same time is on the market.
In this study a mathematical relation between SDI and MFI0.45 has been successfully developed, assuming that cake filtration is the dominant filtration mechanism during the tests. Based on the developed mathematical relation and experiments with an artificial colloidal suspension of aluminum oxide spheres (0.6 μm) as model water, it could be demonstrated that the SDI depends on pressure, temperature and membrane resistance. The effect of temperature and membrane resistance explains to a large extent the erratic results from the field. It is recommended to correcting SDI for temperature and membrane resistance and/or to making the guideline formulated by ASTM for the allowable range of membrane resistances much more stringent.

1. Introduction

Reverse osmosis, nanofiltration, ultra- and microfiltration are well established technologies and are rapidly expanding. Nevertheless these technologies are still hindered in their smooth operation by fouling phenomena. Fouling due to suspended and colloidal matter (particulate fouling) is one of the reasons for this hindrance [1]. Particulates tend to foul the membrane surface (covering the surface and blocking pores), plug the spacer in spiral wound elements, and plug the hollow fiber bundles in reverse osmosis and nanofiltration.

Fouling of the membrane itself results in an increase in membrane resistance and as a result a higher feed water pressure is required to maintain the capacity of the RO/NF plant. In addition the salt passage is expected to increase due to enhanced concentration polarization in the foul layer. Plugging of the spacer results initially in unequal flow distribution and as a result concentration polarization will increase. An increase in head loss across the spacer of a spiral wound element will occur as well, which might eventually damage the element seriously. To control the effects of fouling, (frequent) cleaning might be necessary, which affects negatively the robustness of this technology, shortens the life time and generates direct and indirect extra operational cost.

Estimating the fouling potential is a prerequisite to control membrane fouling successfully. For this purpose two different tests are used, i.e. the Silt Density Index (SDI) and the Modified Fouling Index (MFI0.45). In both tests membranes with pores of 0.45 μm are used and measure the rate of flux decline at constant pressure. In principle these tests can be done by making use of the same equipment [2,3].

SDI is an empirical test initially developed by Dupont Permasep to characterize the fouling potential of their hollow fine fiber elements. The SDI test is applied worldwide for many years because it is cheap

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and simple, which explains that this test is done as a routine basis by operators. It is currently considered as the ultimate test to measure the fouling potential of feed water for reverse osmosis and nanofiltration membranes. However, there are growing doubts about the reliability of this test e.g. several manufacturers of micro- and ultrafiltration membranes are frequently confronted with the phenomenon that the filtered water does not meet the requirement and that the SDI should be lower than 3 [4]. From a theoretical point of view it is hard to explain that water filtered through membranes with pores smaller than 0.02 µm has an SDI higher than 3.

These observations might be attributed to deficiencies of the SDI test e.g. the test is not corrected for variations in pressure, temperature, and pore size and membrane resistance of the used filters. Moreover the test is not based on any filtration mechanism and as a consequence there is no linear relation between SDI and the particulate matter concentration. Due to the SDI deficiencies, in the most recent standard (D 4189-07) ASTM mentioned that SDI is not applicable for the effluents from most RO and UF systems.

Although the SDI test is widely used, there is growing doubt about the value of the SDI test as a predictive tool for RO membrane fouling [5–7]. These doubts consist of two aspects: 1) the relation between the SDI value and the performance of the RO unit, and 2) the SDI deficiencies.

Due to the inability to capture fine colloids, fouling rates predicted from the SDI test for RO feed water were far too low [8,9]. It was therefore hypothesized that smaller colloidal particles were responsible for the observed flux decline rates in RO [10]. In RO, membranes with no distinct pores are used, while the process operates with a cross-flow system and uses spacers to separate the membranes. On the contrary, the SDI test uses a 0.45 µm microfiltration membrane in a dead-end filtration experiment. Particles much smaller than 0.45 µm easily can foul the RO membrane and the spacers. Since the 0.45 µm MF membrane used for SDI determination is unable to capture those particles, the SDI value may have no strong correlation with RO fouling.

To overcome the main deficiencies of the SDI, the MFI0.45 has been developed by Schippers et al. This test is based on cake filtration, and is corrected for pressure and temperature [6,11–13]. Measurements needed for determining MFI0.45 are less simple than for the SDI test that is why MFI0.45 measurements are usually not done by operators. By definition the MFI should be corrected for the testing conditions (T, dP, A_M). The membrane resistance correction for MFI was initially proposed with an empirical equation by Heijman et al. [14]. Fully automated equipment measuring SDI and MFI0.45 at the same time, is on the market.

The aim of this study is to reveal potential reasons for the erratic results in measuring the SDI, obtained in practice when characterizing the fouling potential of water pre-treated with ultra- and microfiltration plants. Objectives are:

– to develop a mathematical relation between SDI and MFI0.45 to make it possible to demonstrate the effect of pressure, temperature and membrane resistance on SDI. In addition, such a relation might be useful in practice to convert the MFI0.45 values into SDI values;
– to measure the effect of pressure, temperature and membrane resistance on the SDI with a colloidal suspension of aluminum oxide particles.

This work was performed with an α-Alumina suspension as model water. The proposed SDI/MFI relation was proven to be valid on real seawater too, as will be discussed in a forthcoming paper [15].

2. Theoretical background

In this study the focus will be on the two main fouling indices SDI and MFI0.45. ASTM International describes the standard procedure for SDI. More specifications for the equipment and the microfiltration membrane filters for this test were added to the most recent version of ASTM. MFI0.45 has been introduced and described by Schippers and Verdouw in 1980 [6].

2.1. Silt Density Index

To determine the SDI, the rate of plugging of a membrane filter with pores of 0.45 µm at 30 psi (207 kPa) is measured. The measurement is done as follows;

a) The time t_1 is determined which is required to filter the first 500 mL.
b) 15 min (t_f) after the start of this measurement time t_2 is measured which is required to filter 500 mL.
c) The index is calculated with the following formula.

$$SDI = \frac{100\%}{t_f}\left(1-\frac{t_1}{t_f}\right) = \frac{\%P}{t_f} \tag{1}$$

Where SDI is the Silt Density Index (%/min), t_f is the elapsed filtration time (min) after the start of collecting the first 500 mL, t_1 is the time required to collect the first 500 mL and t_2 is the time required to collect the second 500 mL after 15 min (or less). If the plugging ratio $\%P$ is exceeding 75%, a shorter period t_f has to be taken e.g. 10, 5 or 2 min.

By rearranging the formulae it can be shown easily that the SDI measures the decline in filtration rate expressed as “percentage” per min [16].

2.2. Modified Fouling Index

The Modified Fouling Index (MFI0.45), derived by Schippers and Verdouw in 1980 [6] from the SDI, was aimed to measure the fouling potential of feed water for reverse osmosis installations. For determination of the MFI0.45, the flow through the membrane filter is measured as a function of time.

These data are processed with Eq. (2) which follows from the theory of cake filtration

$$\frac{t}{V} = \frac{\mu \cdot R_M}{dP \cdot A} + \frac{\mu \cdot I}{2 \cdot \Delta P \cdot A_M^2} . V \tag{2}$$

Where

V accumulated filtrate volume (L or m^3)
t time (s)
A_M membrane area (m^2)
dP applied pressure (Pa)
μ water viscosity (Pa s)
R_M clean membrane resistance (m^{-1})
I fouling potential index (m^{-2}).

The MFI0.45 is derived from the slope in the relation t/V versus V and given in Eq. (3). This slope $tg\alpha$ is by definition equal to MFI0.45, when it has its minimum and under the conditions that the temperature is 20 °C, the pressure is 30 psi (207 kPa) and the membrane surface area equals $13.8 \times 0{-}^{4}\ m^2$ (47 mm diameter). The MFI0.45 is corrected for T and P using Eq. (4), and is therefore independent of temperature and pressure. The minimum value for $tg\alpha$ is by definition MFI0.45, since at the start the filtration mechanism is frequently pore blocking resulting in a high slope. Subsequently cake filtration starts and becomes gradually the governing mechanism until cake compression starts, resulting in an increasing slope. Fig. 1(a) shows $tg\alpha$ calculated out of the t/V versus V curve. Fig. 1(b) shows that the fouling index $tg\alpha$ is dependent on time, and that the minimum value of $tg\alpha$ equals the MFI.

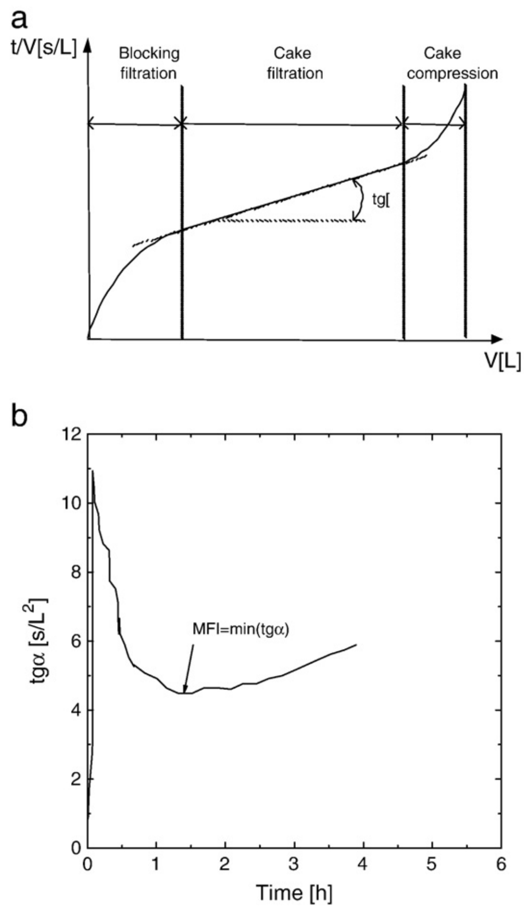

Fig. 1. (a) *tgα* calculated out of the *t*/*V* versus *V* curve, (b) fouling index *I* curve. Redrawn from Ref. [8].

MFI0.45 is expressed in s/L^2 to get values which are in the same order of magnitude as SDI.

$$tg\alpha = \frac{\mu \cdot I}{2 \cdot dP \cdot A_M^2}. \tag{3}$$

MFI0.45 could be calculated with the following formula: [8]

$$MFI = tg\alpha \times \frac{\mu_{20}}{\mu} \times \frac{dP}{dP_0} \times \left(\frac{A_M}{A_{M0}}\right)^2. \tag{4}$$

Where,

μ_{20} water viscosity at 20 °C [Pa s],
A_{MO} reference membrane area 13.8×10^{-4} [m^2] and
dP_O reference applied pressure 2.07×10^5[Pa]

The water viscosity at a temperature T (in °C) is calculated using the following empirical equation [17–19].

$$\mu = 0.497 \times (T + 42.5)^{-1.5} \tag{5}$$

Where

T temperature [°C].

2.3. Standard ASTM

In the most recent ASTM International 'Standard Test Method for Silt Density Index (SDI) of Water' [20] the following membrane properties are recommended to be used in the test: membrane white hydrophilic, mixed cellulose nitrate (50–75%) and cellulose acetate (MCE); mean pore size 0.45 μm. Diameter 47 mm nominal, plain; size 25 mm or 90 mm diameter also can be used. Thickness is between 115 and 180 μm. Pure water flow time 25–50 s for 500 mL under applied pressure difference 91.4–94.7 kPa. Bubble point 179–248 kPa; use only filters that are packaged in the same orientation.

If the plugging ratio %P is exceeding 75% a shorter period t_f has to be taken e.g. 10, 5 or 2 min.

3. Materials and methods

3.1. Silt Density Index test procedures

The procedure for measuring the SDI has been standardized by ASTM [20]. Accordingly, equipment and procedures used are as discussed later.

The apparatus was assembled as shown in Fig. 2. The feed pump was automatically controlled to provide a constant feed pressure of 207 ± 7 kPa (30 ± 1 psi). Before installing the membrane filter, the water to be tested was flushed through the apparatus in order to remove entrained contaminants. The water temperature was measured and kept constant throughout the test. An MF 0.45 μm membrane filter (25 mm in diameter) was placed on the support plate of the holder. The membrane filter was touched only with tweezers to avoid puncturing or contamination. It was checked whether the O-ring was in a good condition and properly placed. The trapped air was bled out through the relief air valve added to the filter holder. The flow rate was measured using the flow meter (connected to a PC). The times to collect the first sample t_1 and the second sample t_2 were calculated using the filtration collected data (time versus volume). The SDI is calculated using Eq. (1).

In this research a sampling period of 15 min t_f has been used, since the plugging in the test was usually less than 75%.

According to the ASTM standard, the volumes to be collected are 500 mL, which is based on a 47 mm membrane diameter. Three membrane diameters of 47, 25 and 90 mm were mentioned in the ASTM standard to be used. The sample volumes for those standard diameters are 500, 141.5 and 1833.4 mL, respectively.

3.2. Modified Fouling Index

For determination of the MFI0.45, the equipment in Fig. 2 was used to measure the flow with intervals of 10 s. The MFI0.45 has been calculated according to the procedures described in Ref. [6].

3.3. Membrane

Eight types of 0.45 μm MF membranes were chosen for this study as shown in Table 1, including the membrane filters meeting the ASTM standard (M4, M6, and M7).

3.4. Colloidal suspension as model water

α-Alumina hydrophilic particles (AKP-15, Sumitomo Chemical, Tokyo, Japan) were used, having a particle size of 0.6 μm and an isoelectric point (IEP) at pH 9 [21]. The AKP-15 has narrow particle size distribution. The colloidal suspensions were prepared in demineralized water, purified by a Synergy SYNS Ultra-Pure system (Millipore). To avoid any settling the suspensions were well mixed using a mechanical mixer in the feed tank.

3.5. Measured and calculated SDI

During the SDI test, the filtration data t and V will be collected. The time t_1 and t_2 for collecting the samples V_1 and V_2 will be

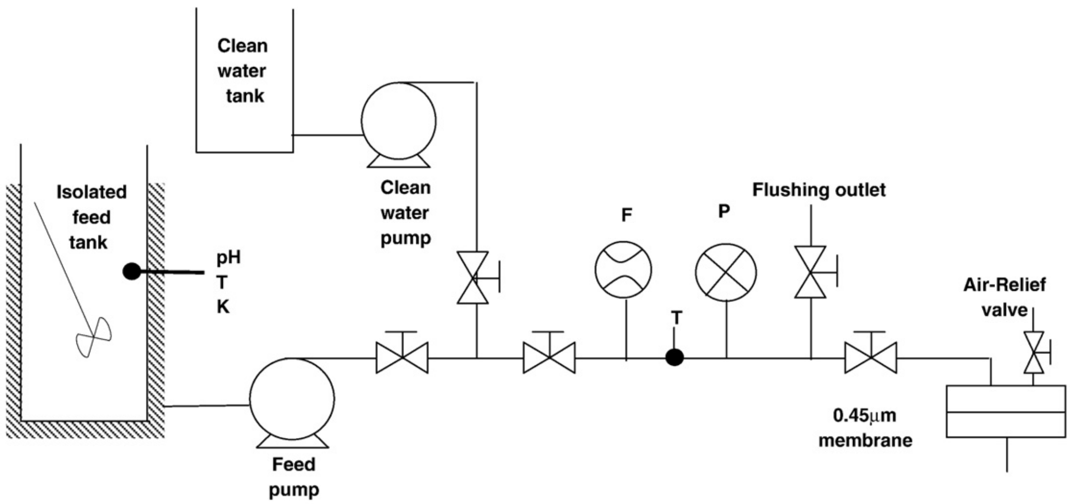

Fig. 2. Flowsheet of the SDI setup. Feed tank and clean water tank are shown. pH, temperature (T) and conductivity (K) are measured in the feed tank as well as in the feed line. Pressure (P), flow rate (F) and temperature (T) are measured in the feed line.

measured. Furthermore, the testing condition parameters (T, dP, R_M) will be recorded during the SDI test. The SDI-measured will be determined using Eq. (1). The fouling parameters I will be estimated from the curve of t/V versus V. The SDI-calculated will be determined using the fouling model which will be developed in Section 4.1. SDI-measured and SDI-calculated will be compared (Fig. 3).

Table 1
Microfiltration membranes used in this work. Pore size as given by the manufacturer. R_M is the average measured clean water resistance (20 °C).

Code	Material	Nominal pore size [μm]	R_M [$\times 10^{10}$ 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 material.

4. Results and discussion

4.1. Mathematical relation between SDI and MFI0.45

The development of the mathematical relation between SDI and MFI0.45 is based on the assumption that only cake filtration occurs during the whole test. To determine the SDI from a model, two functions are needed: a function describing the volume filtered in a certain time period: $V(t)$ and a function describing the time required to filter a certain volume: $t(V)$.

The starting point is Eq. (1) which is used to calculate the SDI. In this equation t_1 and t_2 need to be determined, while t_f can be chosen. The relation between the different parameters is given:

$$\begin{aligned} t_1 &= t_1(V_1) \\ V_f &= V\left(t_f\right) \\ t_{\text{total}} &= t_{\text{total}}\left(V_f + V_2\right) \\ t_2 &= t\left(V_f + V_2\right) - t\left(V_f\right). \end{aligned} \tag{6}$$

Where:

t_1	is the time to collect the volume V_1;
t_2	is the time to collect the volume V_2 which is equal to V_1; it is called V_c which is the collected filtrate volume in time t_1 or t_2;
V_f	is volume collected in t_f;
t_{total}	is time to collect the volume $V_f + V_2$.

The parameters mentioned earlier are derived from Eqs. (1), (2), and (4) according to the following steps.

1. t_1 follows from Eq. (7):

$$t(V) = \frac{\mu \cdot R_M}{dP \cdot A_M} \cdot V + \frac{\mu \cdot I}{2 \cdot dP \cdot A_M^2} V^2 \tag{7}$$

2. Since t_2 cannot be determined directly, a couple of steps are needed.
3. For calculating t_2, first an equation has been derived from Eq. (2) to obtain V as a function of t:

$$V(t) = \frac{-\mu \cdot R_M + \sqrt{\mu^2 \cdot R_M^2 + 2 \cdot I \cdot dP \cdot t}}{I \cdot \mu} \cdot A_M \tag{8}$$

4. $V_{\text{total}} = V_f + V_2$ (V_{total}, V_f and V_2 are the volumes filtered in respectively t_{total}, t_f and t_2)
5. By substitution of t_f for t in Eq. (8) one obtains V_f;
6. Substitution of V_t in Eq. (7) gives t_f;
7. t_2 follows from $t_2 = t_{\text{total}} - t_f$;
8. Substitution of t_1 and t_2 in Eq. (1) results in Eq. (9):

$$SDI = \frac{100}{t_f(\text{min})} \left(1 - \frac{\frac{\mu \cdot R_M}{dP \cdot A_M} \cdot V_c + \frac{1}{2} \cdot \frac{\mu \cdot I \cdot V_c^2}{dP \cdot A_M^2}}{\left(\frac{\mu \cdot R_M}{dP \cdot A_M} \left(V_c + \frac{\left(-\mu \cdot R_M + \sqrt{\mu^2 \cdot R_M^2 + 2 \cdot \mu \cdot I \cdot dP \cdot A_M \cdot t_f}\right) \cdot A_M}{\mu \cdot I} \right) + \frac{1}{2} \frac{\mu \cdot I}{dP \cdot A_M^2} \left(V_c + \frac{\left(-\mu \cdot R_M + \sqrt{\mu^2 \cdot R_M^2 + 2 \cdot \mu \cdot I \cdot dP \cdot A_M \cdot t_f}\right) \cdot A_M}{\mu \cdot I} \right) \right)} \right). \tag{9}$$

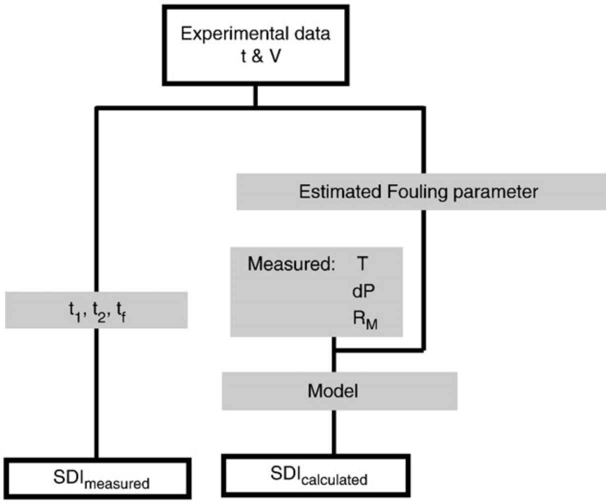

Fig. 3. Diagram of SDI (measured) and SDI (calculated).

Where:

I	fouling potential index [m^{-2}]
V_c	volume of the first and second sample $V_c = V_1 = V_2$ [m^3]
A_M	membrane area [m^2]
t_f	elapsed filtration time (15 [min] or 900 [s])
dP	applied pressure [Pa]
μ	water viscosity [Pa s]

Eq. (9) can be used to model the SDI results, however, this relation is limited to the cake filtration mechanism and 100% particle rejection. Eq. (9) is not valid in case of cake compression.

Fig. 4 illustrates schematically the determination steps for SDI from a time–volume curve.

This equation demonstrates that SDI depends on pressure, temperature and membrane resistance. SDI/MFI0.45 relation can be demonstrated by substitute Eqs. (3) and (4) in Eq. (9).

4.2. Relation between the SDI and concentration of a colloidal suspension

The MFI0.45 has a linear relation with particle concentrations as proved by Schippers and Verdouw [6]. On the contrary SDI has a non-

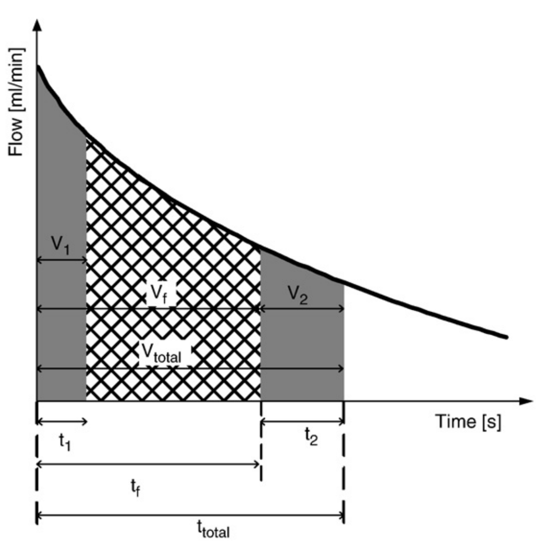

Fig. 4. Schematic filtration diagram for calculation of the SDI out of the measured flow–time curve. V_1 and V_2 are the shaded areas under the curve.

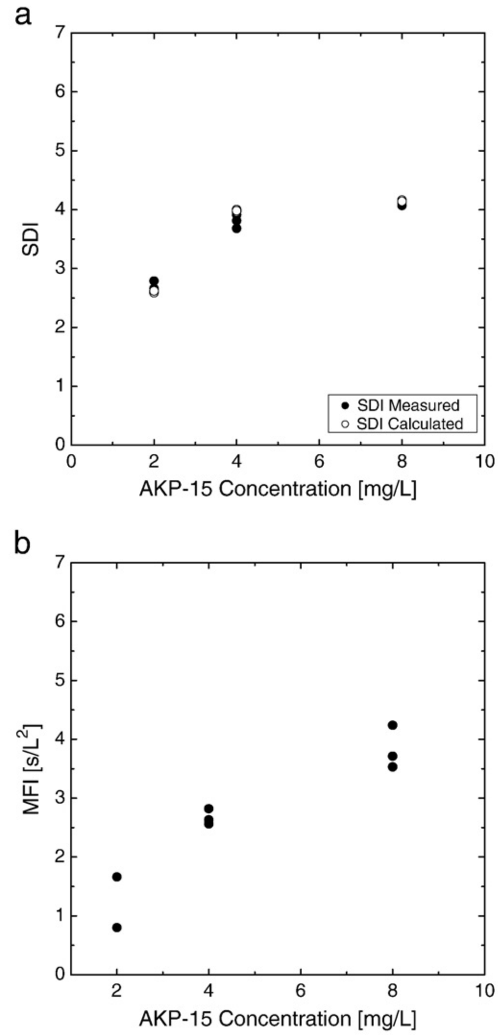

Fig. 5. (a) Experimental and theoretical SDI (SDI-measured and SDI-calculated) results. (b) MFI0.45 for three colloidal suspensions (2, 4 and 8 mg/L) of α-Alumina particles (AKP-15) with 0.6 μm size. The filtration experiments were carried out using cellulose acetate membrane M7 (25 mm diameter).

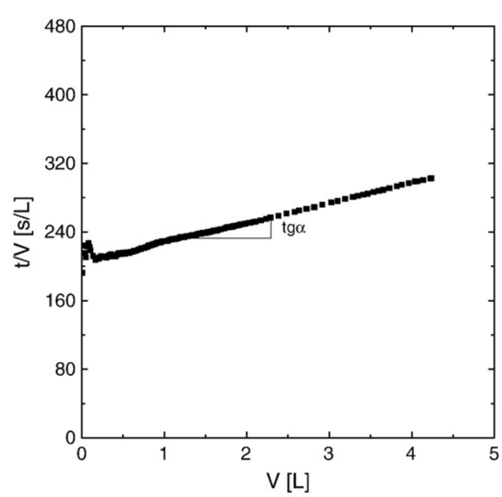

Fig. 6. *tgα* calculated out of the *t*/*V* versus *V* curve. Filtration test of 4 mg/L AKP-15 particle solution in ultra-pure water using M7 (25 mm diameter). The test was under a constant pressure difference (*dP*) of 207 kPa and a temperature (*T*) of 20 °C.

Table 2
The deviation in SDI value due to ± 7 kPa variation in dP_O for different SDI levels.

SDI (dP_O kPa)	SDI ($dP_O + 7$ kPa)	SDI ($dP_O - 7$ kPa)
1	1.03	0.98
2	2.04	1.97
3	3.04	2.96
4	4.04	3.96

linear relation with the particle concentration as demonstrated in Fig. 5(a). In this figure the results of nine SDI test are shown, which were performed at a constant temperature of 21.5 °C and a constant pressure of (207 kPa) for three AKP-15 particle concentrations: 2, 4 and 8 mg/L. Three SDI tests for each concentration were carried out using the cellulose acetate membrane (M7) diameter 25 mm.

The linear relationship between MFI0.45 with the particle concentration was confirmed by Schippers and Verdouw [6]. However, in Fig. 5 (b) the relation between MFI0.45 and particle concentration is not a perfect linear relationship, which might be due to a particle rejection unequal to 100%. The difference between the SDI-measured and SDI-calculated is marginal and indicates that cake filtration is dominant. This conclusion is supported by Fig. 6 showing t/V versus V, having an almost linear relation. The effect of different fouling mechanisms on the SDI will be presented in a future article [22].

4.3. Effect of applied pressure

The ASTM procedure requires a constant pressure difference over the membrane of 207 kPa (± 7 kPa) during the SDI test. To demonstrate the theoretical effect of different applied pressures, Eq. (9) was used at different values of MFI0.45 (0.2–10 s/L^2). The reference parameters assumed were: feed temperature 20 °C, membrane resistance R_M 1.29×10^{10} m^{-1} and membrane area A_M 13.8×10^{-4} m^2.

Table 2 shows that the ASTM allowable range of dP (± 7 kPa) results in an SDI deviation of $\approx \pm 0.04$.

Fig. 7 shows the results of the calculated SDI as a function of the pressure. The higher the pressure, the higher the SDI. At low MFI0.45 (i.e. a low particle concentration), the influence of the applied pressure in SDI is higher (higher slope).

To verify the results of these calculations the effect of pressure was measured experimentally. For this purpose SDI tests were carried out using membrane M7 and a suspension of α-Alumina particles (AKP15) at various pressures: 0.5, 2.07 and 3 bar (50, 207 and 300 kPa). All the experiments were performed at room temperature (20 °C).

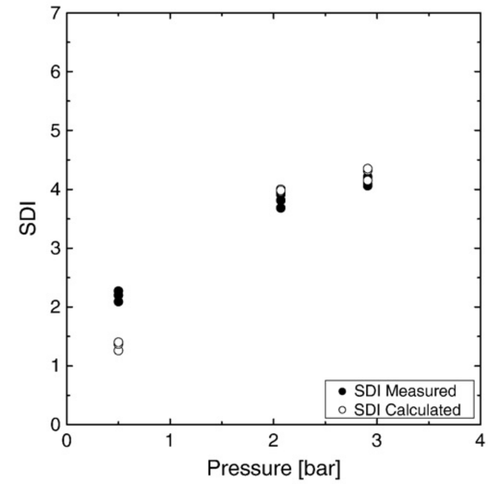

Fig. 8. SDI theoretical and experimental results for different applied pressures (50, 207 and 300 kPa) with an AKP-15 particle concentration of 4 mg/L.

Fig. 8 shows that the experimental results are in good agreement with the theoretical predictions at 207 and 300 kPa. At 50 kPa however, the results are lower than the experimental results. Fig. 7 shows that the slope of the SDI/dP relation decreases with increase dP. Therefore, the deviation between the measured and calculated SDI might be attributed to the high sensitivity of SDI for error at low SDI values. Furthermore, at low dP the fouling load arrived to the membrane surfaces lower than high dP case. This relaxation affects the cake formation time and density which influence SDI value as well.

4.4. Effect of temperature

Based on Eq. (9) the effect of temperature on SDI was studied for assumed MFI0.45 values at a membrane resistance R_M of 1.29×10^{10} m^{-1}, a membrane area A_M of 13.8×10^{-4} m^2 and constant pressure difference dP of 207 kPa. Fig. 9 demonstrates that the SDI increases with increasing

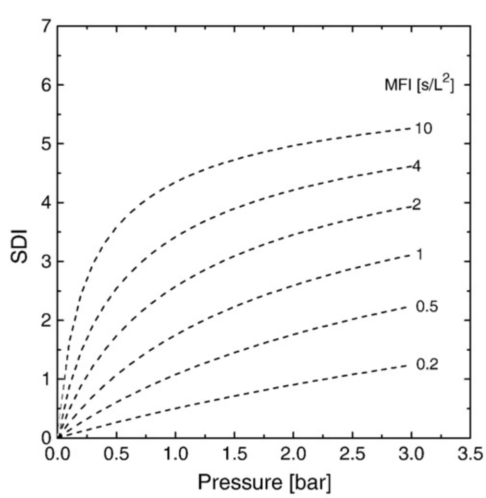

Fig. 7. Theoretical SDI results for different applied pressures (dP) and different MFI0.45 values (0.2–10 s/L^2). The calculation is carried out with reference parameter membrane resistance (R_M) 1.29×10^{10} m^{-1}, membrane area (A_M) 13.8×10^{-4} m^2 and feed temperature 20 °C.

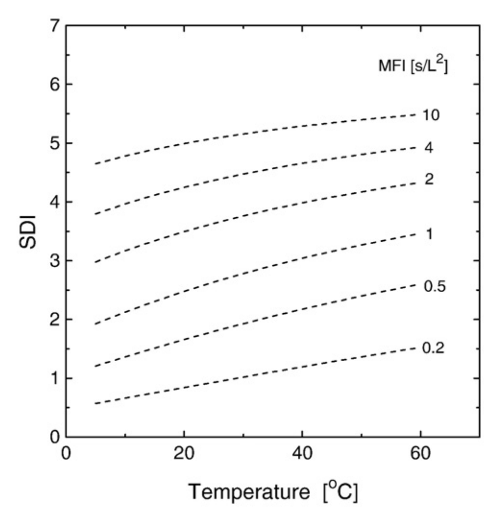

Fig. 9. Theoretical SDI results for different temperatures (T) and different MFI0.45 values (0.2–10 s/L^2). The calculation is carried out with the following reference parameters: a membrane resistance (R_M) of 1.29×10^{10} m^{-1}, a membrane area (A_M) of 13.8×10^{-4} m^2 and a constant applied pressure difference (dP) of 207 kPa.

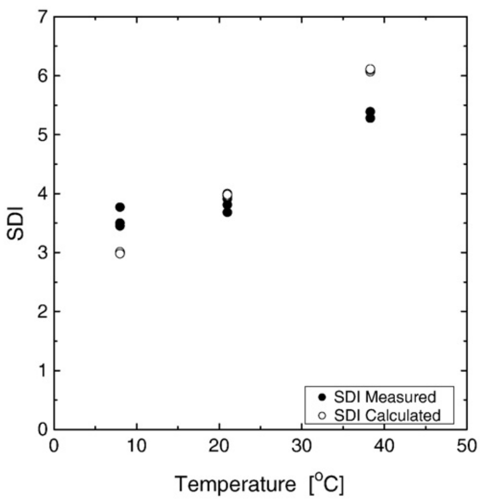

Fig. 10. Calculated and measured SDI values for different 8, 22 and 38 °C of a colloidal suspension of 4 mg/L of AKP-15.

temperature. This effect is because of the temperature dependency of the viscosity.

In the desalination field, RO plants might operate either in hot areas (e.g. in the Middle East up to 40 °C) as well as in cold areas (e.g. in Europe down to 5 °C). Consequently, the SDI results need to be corrected for the feed water temperature in order to compare them.

To verify the predicted results experimentally, the SDI of a colloidal suspension of 4 mg/L α-Alumina particles (AKP15) has been measured using membrane M7 at different feed temperatures (8, 22, and 38 °C). Three SDI tests were carried out for each temperature. The results of these experiments and the theoretical prediction of the SDI are shown in Fig. 10.

Theoretical results are in good agreement at 22 °C. However, at 8 °C and 38 °C the theoretical results deviate from the experimental results. The artifacts that happened during the test affect the SDI value. The sensitivity for error is higher at low T than high T. However, the foulants–foulants and foulants–membrane interaction was not cooperated in the modeling calculation for SDI.

4.5. Effect of the membrane resistance

4.5.1. ASTM allowable range for R_M

In order to demonstrate the effect of the membrane resistance on SDI, the following reference testing parameters were set: A_M 13×10^{-4} m^2, T 20 °C and dP 207 kPa. The SDI/MFI0.45 relation is shown in Fig. 11(a) for different membrane resistances: the ASTM allowable range 0.86–1.72 × 10^{10} m^{-1}, and the range for what is available in the market 0.39–2.65 × 10^{10} m^{-1}. Fig. 11(a) demonstrates a very pronounced effect of membrane resistance on the SDI value. As a consequence the SDI value for water with a fouling potential of MFI0.45 = 2 might vary between 1.7 and 5.6 depending on a membrane resistance between 0.86 × 10^{10} and 1.72 × 10^{10} m^{-1} (the ASTM standard). The pure water flow guidelines set by the ASTM, indirectly for the resistance of the used membranes, are much too broad to ensure correct and comparable SDI values.

The ASTM wide range of allowable membrane resistances explains at least at part of the frequently reported erratic results in practice. Table 3 shows the influences of ± 10% and ± 20% on the SDI results. From a practical point of view, the influence of 10% in R_M results in SDI deviation with ≈±0.26 at SDI = 3 is acceptable. Therefore, to avoid the SDI deficiency of the SDI it is recommended to narrow the allowable range to the reference R_{MO} value 1.29 × 10^{10} m^{-1} ± 10%.

Fig. 11(b) shows the deviation in SDI values as result of ASTM range, available range in the market, 10% and 20% variation in R_{MO}.

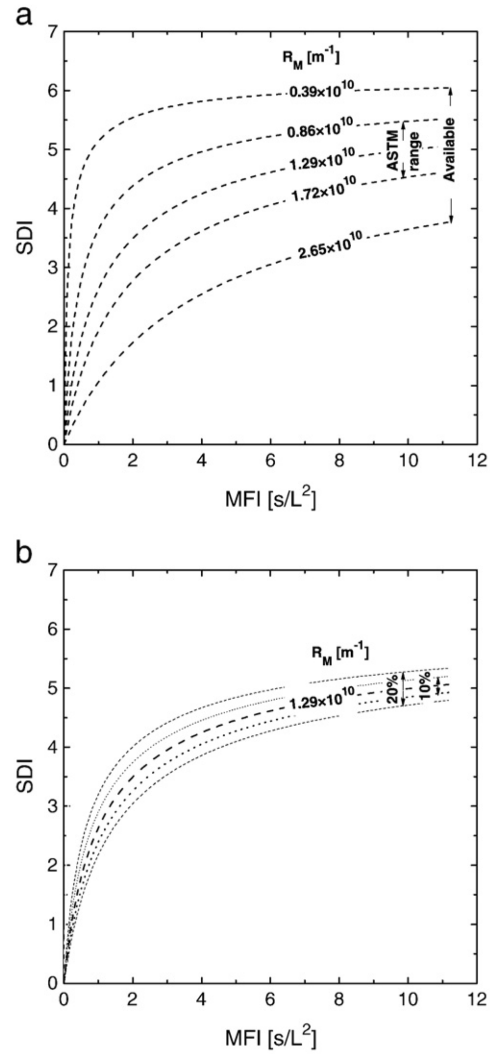

Fig. 11. The mathematical relation between SDI and MFI0.45 as a function of the membrane resistance. (a) ASTM range: 0.86 × 10^{10} to 1.72 × 10^{10}. Range of what is available in the market: 0.39 × 10^{10} to 2.65 × 10^{10} m^{-1}. (b) Suggested allowable range: ± 10%, ± 20% of R_{MO} 1.29 × 10^{10} m^{-1}. Reference parameters assumed: a membrane area (A_M) of 13.8 × 10^{-4} m^2, a temperature of 20 °C and a pressure difference (dP) of 207 kPa.

4.5.2. Experimentally determined effect of membrane resistance

To demonstrate experimentally the effect of the membrane resistance on SDI, different membranes made of different materials and by different manufactures were used. In the tests a colloidal suspension of 4 mg/L α-Alumina particles (AKP-15) was applied. The temperature was 21 °C and the pressure was 207 kPa. The measured SDI results were plotted versus the membrane resistance in Fig. 12. Besides that, the fouling index I was calculated for each experiment. Subsequently Eq. (9) was used to calculate the theoretical SDI values for each experiment.

The theoretically and experimentally determined relation between membrane resistance with SDI are in good agreement and

Table 3
The deviation in SDI value due to the ASTM range and ± 10%, ± 20% variation in R_{MO}.

SDI (R_{MO})	SDI (R_{MO} ± 10%)	SDI (R_{MO} ± 20%)	SDI (R_{MO} ASTM range)
1	0.86–1.18	0.71–1.40	0.60–1.81
2	1.79–2.26	1.60–2.65	1.38–3.00
3	2.76–3.26	2.54–3.55	2.29–3.98
4	3.79–4.23	3.59–4.46	3.34–4.78

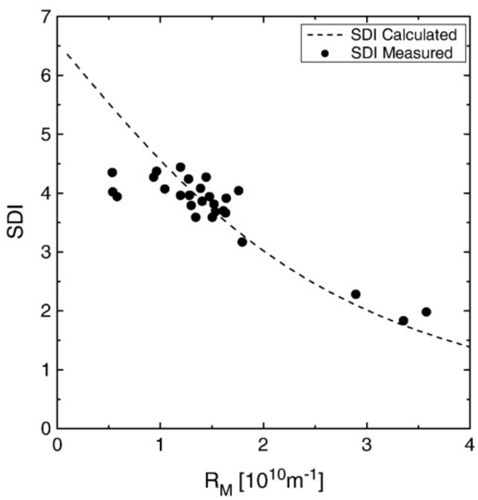

Fig. 12. SDI experimental and theoretical results as a function of the membrane resistance for different membranes. The experiments were carried out using a particle concentration of 4 mg/L AKP-15 and a pressure difference of 207 kPa.

show a strong dependency of the membrane resistance, e.g. increasing the membrane resistance from 0.5×10^{10} m^{-1} to 3.5×10^{10} m^{-1} results in a reduction of the SDI from 4.5 to 2 for the same water quality. At low R_M, the measured SDI values that deviate from the calculated SDI may be due to the SDI sensitivity for error and artifacts.

This tremendous effect has to be attributed to the fact that the rate of filtration, and consequently the fouling load, depends on the resistance of the membrane used.

In the SDI test the time between the two measurements is fixed and the 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 incrementally and consequently the measured SDI. This explains our observation that the SDI increases with increasing temperature (decreasing viscosity so increasing flow), increasing pressure and decreasing membrane resistance.

4.5.3. Equivalent MFI0.45 value for SDI15 = 3

In practice it is commonly accepted that the SDI of RO feed water preferably should be lower than 3. Taking into account the deficiencies in the SDI method, the MFI0.45 method is to be preferred. Besides the less simple procedure, the other hurdle needs to be taken is defining a similar guideline like SDI<3 for MFI0.45.

In principle this guideline can be simply derived for e.g. SDI = 3 by making use of Eq. (9). However doing so it will turn out that it is not possible to get one distinct guideline value. The reason is that the SDI strongly depends on the membrane resistance. This effect is illustrated in (Fig. 13) showing the calculated MFI0.45 values for SDI = 3. This means that a wide range of MFI0.45 values are equivalent to SDI = 3. Limiting the range of allowable membrane resistances according to ASTM reduces the equivalent MFI0.45 guideline to the range of 0.6 to 2.4 s/L^2. This situation again clearly demonstrates the need of narrowing down the allowable range of resistances of the applied membranes.

4.6. Normalizing SDI

Large deviations might occur in measuring the SDI, due to differences in membrane resistance, temperature and pressure. These observed variations are unacceptably large. So it is recommended to reduce these variations by normalizing the obtained results. The mathematical bridge SDI/MFI0.45 in Eq. (9) gives can be used for this purpose. Normalizing needs to define reference values for the testing parameters. The following reference parameters are suggested:

- Membrane resistance R_{MO} — 1.29×10^{10} [m^{-1}], the average of ASTM range
- Feed temperature T — 20 [°C]
- Applied pressure dP_O — 207 [kPa].

The proposed correction is based on the assumption that cake filtration occurs and effects of variations in rejection can be neglected. However it is well known that during the SDI test, initially pore blocking occurs. The length of these periods varies with the type of particulate matter e.g. particle size distribution. Furthermore it is known that particles smaller than 0.45 μm are passing at least partly the membrane filters. During filtration a part of these particles might be rejected, due to narrowing of the pores and/or formation of the cake. This means that the proposed normalization will improve the accuracy and reproducibility of the SDI, but that the proposed corrections are not fully covering reality.

Reducing the allowable range of the membrane resistance might be useful to eliminate at least the dramatic effect of variations in the membrane properties. From a practical point of view, it is reasonable to use a membrane with a resistance of 1.29×10^{10} m^{-1} and allowing variations of $\pm10\%$ and acceptable variation in SDI ±0.25 at a level of SDI = 3. Additional studies on normalizing SDI are ongoing and will be published in a following paper.

5. Conclusion and recommendations

A mathematical relation between SDI and MFI0.45 has been developed. This relation is valid under the conditions that cake filtration occurs during the whole filtration test and variations in rejection have no effect on the SDI/MFI0.45 results.

Based on this relation and experiments the following can be concluded:

- The SDI depends on pressure, the higher the pressure the higher the SDI;
- A pronounced effect of temperature exists;
- The membrane resistance has a very dominant effect on the SDI.

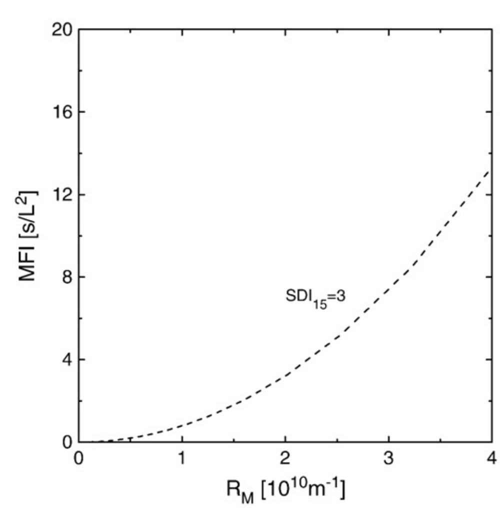

Fig. 13. Equivalent MFI0.45 values for SDI = 3 for different membrane resistances (R_M). The calculations were performed with the following reference parameters: an applied pressure difference of 207 kPa, a feed temperature of 20 °C and a membrane area of 13.8×10^{-4} m^2.

A higher membrane resistance results into dramatically lower SDI values. The indirectly formulated guideline by ASTM for an acceptable range for membrane resistance R_M (between $0.86\times10^{10} < R_M < 1.72\times10^{10}\ m^{-1}$) is far from adequate. The allowable variations in membrane resistance are responsible for values of the SDI between 2.29 and 3.98 at a level of SDI = 3.

It is therefore recommended:

- to narrow the resistance range to e.g. $1.29\times10^{10}\ m^{-1}\pm10\%$ ($1.16\times10^{10} < R_M < 1.42\times10^{10}$); this range results in deviations of ±0.25 in SDI value (at SDI = 3);
- to correct the SDI for temperature and membrane resistance.

The effects of temperature and variations in membrane resistance on SDI explain to a large extent the erratic results reported in practice. Therefore, there is a strong need for normalization.

This work was performed with a model water consisting of an α-Alumina suspension. However, the proposed SDI/MFI relation was proven to be valid for real seawater too as will be presented in a future paper [15]. The effect of different fouling mechanisms on the SDI will be shown in a forthcoming article [22].

Nomenclature

A_M	Membrane area [m^2]
A_{M0}	Reference membrane area 13.4×10^{-4} [m^2]
dP	Applied pressure [Pa]
dP_O	Reference applied pressure 207 [kPa]
I	Fouling potential index (cake filtration constant) [m^{-2}]
MFI0.45	Modified Fouling Index [s/m^6] or [s/L^2]
%P	Plugging ratio [%]
R_M	Membrane resistance [m^{-1}]
R_{MO}	Reference membrane resistance 1.29×10^{10} [m^{-1}]
SDI	Silt Density Index [%/min]
$t_{1,2}$	Time to collect the first and second samples [s]
t_{15}	Elapsed filtration time 15 [min] or 900 [s]
$tg\alpha$	Minimum slope in the relation t/V versus V [$s\ m^{-6}$]
T	Temperature [°C]
T_o	20 [°C]
V_f	Filtered volume in t_f time[m^3], t_f can be 5, 10 or 15 min
$V_{1,2,C}$	Sample volume [m^3]
μ	Water viscosity, [Pa s]
μ_{20}	Water viscosity at T_o °C [Pa s]
K	Conductivity [$S\ m^{-1}$]

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