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# SDI: is it a reliable fouling index?

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**ABSTRACT**

The ASTM considers the silt density index (SDI) test as a standard test for fouling potential of RO and NF feed waters. Up to date, the SDI is used at many full- and pilot-scale installations. The design and choice of the applied RO pretreatment is to a large extent based on the SDI test on the raw feed water. Comparing and monitoring UF/MF membrane performance is another SDI application. From a practical point of view, the SDI of RO feed water preferably should be lower than 3. The SDI has several disadvantages making it an unreliable test. The SDI has a non linear relationship with the colloidal concentration in the water and it is not corrected for the feed water temperature. Besides that, the SDI is not based on any filtration model. SDI is trying to simulate the RO fouling using dead-end MF membrane. The modified fouling index (MFI) is another fouling index. The MFI is based on the cake filtration model, can be corrected for pressure and temperature and is therefore used as a promising alternative for the SDI. Nevertheless, the procedure of measuring a MFI is more difficult and not directly suitable for carrying out "in the field". The objective of this study therefore is to determine a theoretical relationship between SDI and MFI, and to validate this with experimental results. This relationship can be used to investigate the influence of membrane and testing parameters on SDI under cake filtration conditions, implying this model is valid for cake filtration mechanism and a particle rejection of 100%. In order to calculate the SDI, the times $t_1$ and $t_2$ for collecting the first and second sample are predicted using the measured MFI value and the MFI definition. In this research, the influence of several parameters (such as temperature, membrane resistance, etc.) on the SDI will be shown. The experimental results show a good agreement with the theoretical work, but only if the cake filtration start builds up directly at the beginning of the experiment. In general, this work clearly demonstrates that SDI currently is not reliable test for RO fouling. Either corrections for the SDI are necessary to give a more reliable index, or a new index has to be developed.

*Keywords:* Fouling index; Silt density index (SDI); Modified fouling index (MFI); Membrane resistance; SDI/MFI mathematical relation; Particle concentration

## 1. Introduction

The membrane technology is relatively new, safe, economic, and environmentally friendly. On the other hand, some problems are present and performance limitation.

One of these problems is related to the presence in feed water of colloidal and suspended matter [1]. These materials tend to foul the membrane surface (covering the surface and blocking pores) plug the

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spacer in spiral wound elements, and plug the hollow fiber 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 RO/NF plant. Plugging of their spacer, results initially 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 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 could be obtained by the performance fouling test. Most of the fouling test is applied under constant pressure. Measuring the flux decline can be estimated by measuring the accumulated of the permeate volume as function of time. Many methods were used to describe the fouling potential such as silt density index (SDI) and modified fouling index (MFI) [2,3].

The SDI and MFI methods, however, reduce the overall and very complex fouling phenomena into a one number value, on which the interpretation of the fouling potential of the feed is based [4].

### 1.1. Standard ASTM fouling index SDI

SDI is an empirical test developed for measuring the rate of fouling of nano filtration (NF) or reverse osmosis (RO) membranes. It represents the potential of membranes fouling by finely suspended particles presents in the feed water.

The procedure for measuring SDI according to the ASTM standard. Simultaneously, the flow rate was measured using the flow meter connected to a PC. The times to collect the samples (141 ml) after 15 min rain of total elapsed flow time were calculated using the filtration collected data. Water temperature has remained constant (±1°C) throughout the test. SDI setup is controlled by software called ViCA, which built on LabView environment by Norit. The SDI is calculated according to the following formula:

$$\mathrm{SDI} = \frac{\left(1 - \frac{t_1}{t_2}\right)\%}{t_f} = \frac{\%P}{t_f} \tag{1}$$

where SDI is the silt density index (% min$^{-1}$); $t_f$ is the elapsed filtration time (min); $t_1$ is the initial time required to obtain the initial sample (second), 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, for example 10, 5 or 2 min.

### 1.2. Modified fouling index MFI

The modified fouling index (MFI), derived by Schippers and Verdouw form the SDI, was aimed to predict the rate of fouling for RO membranes [5]. For determination of the MFI, the equipment in Fig. 1 was used to measure the flow with interval of 10 sec. 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:

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

where $V$ is the filtrated volume (m$^3$); $t$ is the time (s); $A_M$ is the membrane area (m$^2$); d$P$ is the applied pressure (Pa); μ is the water viscosity (Pa s); $R_M$ is the clean membrane resistant (m$^{-1}$); and $I$ is the fouling potential (m$^{-2}$).

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

$$\mathrm{MFI} = \frac{\mu \cdot I}{2 \cdot \mathrm{d}P \cdot A_M^2} \tag{3}$$

### 1.3. Needs for reliable fouling index

SDI test is a simple test to do and doesn't need professionals. This test has some disadvantages which make it an unreliable test. SDI test has some drawbacks: no liner relationship exists between SDI and the colloidal concentration in the water. Beside that, SDI is not based on filtration model. However, SDI is not corrected for temperature, it is not in situ and continuous test. However there is growing doubt about the value of the SDI test as a predictive tool for membrane fouling [5–7].

Conversely, the MFI is based only on the cake filtration mechanism and is dependent on particle size

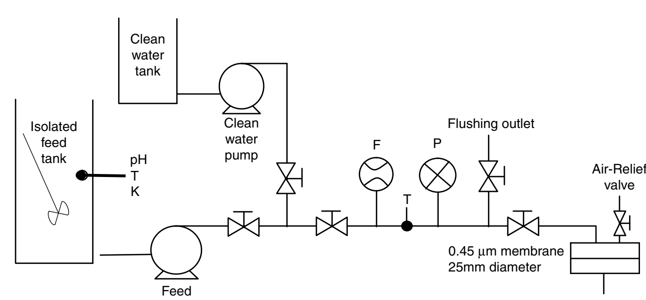


Fig. 1. Flowsheet of the SDI setup. Feed tank and clean water tank are shown. pH, Temperature ($T$) and conductivity ($K$) are measured in the feed tank as well as in the feed line. Pressure ($P$), flow rate ($F$) and temperature ($T$) are measured in the feed line. Valves are controlled using software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

through the Carman–Kozeny equation for specific cake resistance [8]. Thus, in general, smaller particles present in the cake result in higher MFI values. Assuming cake filtration is the dominant mechanism in particulate fouling, the MFI can be used as a basis for modeling flux decline in membrane systems.

However, fouling rates predicted from the MFI measured for RO feed water were far too low. It was therefore hypothesised that smaller colloidal particles were responsible for the observed flux decline rates in RO [9].

Both fouling indices SDI and MFI affected by the variation in the membrane properties available in the market. RO operated with cross-flow system and has spacers between; where SDI and MFI are dead-end filtration experiments. Nevertheless, SDI and MFI are recently the tools to simulate and predict the fouling in the RO [10]. However, in many cases, SDI and MFI could not provide 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 reliable fouling index is growing with the greatest growth in the desalination market. SDI used worldwide even, with the above mentioned drawbacks, makes it unreliable index. However, MFI can be corrected for testing parameters. Effectively, the built mathematical bridge between SDI and MFI can be used to study the effect of testing parameters on SDI through MFI.

Starting with MFI definition, Eq. (2) can be written as:

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

or

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

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

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

or

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

### 2.2. Calculating SDI

In Eq. (1), $t_1$ and $t_2$ to collect $V_1$ and $V_2$ need to be determined to calculate SDI. However, illustrates the mathematical approach to estimate SDI.

Assuming a cake filtration mechanisms and 100% particle rejection, SDI can be calculated using MFI definition. Reference testing parameters were set as follow: $T$ = 20°C, d$P$ = 207 kPa, $A_{\mathrm{M}} = 13.4 \times 10^{-4}$ m$^2$ and $R_{\mathrm{M}} = 1.29 \times 10^{10}$ m$^{-1}$. However, for 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. However, $V_{15}$ can be estimated with Eq. (7) for 15 min. By the end of the filtration experiment, total filtered volume $V_{\mathrm{total}}$ ($V_{15} + V_2$) will be collected. The total filtration time $t_{\mathrm{total}}$ for filtering $V_{\mathrm{total}}$ can be estimated with Eq. (7). Fact, the required time $t_2$ to collect the second volume $V_2$ after 15 min can be calculated as: $t_2 = t_{\mathrm{total}} - 15$ min. Finally, $t_1$ and $t_2$ were used in Eq. (1) to determined SDI. Similarly, the fouling potential I can be used to estimate SDI with equations. SDI can be directly calculated as a function of MFI with the following formula:

$$\mathrm{SDI} = \frac{20}{3}\,\frac{V_2^2 \cdot \mathrm{MFI} \cdot \mathrm{d}P \cdot A_{\mathrm{M}} + V_2 \cdot \sqrt{\mu^2 \cdot R_{\mathrm{M}}^2 + 4 \cdot t_{15} \cdot \mathrm{MFI} \cdot \mathrm{d}P^2 \cdot A_{\mathrm{M}}^2} - \mu \cdot R_{\mathrm{M}} \cdot V_1 - \mathrm{MFI} \cdot V_1^2 \cdot \mathrm{d}P \cdot A_{\mathrm{M}}}{V_2\left(V_2 \cdot \mathrm{MFI} \cdot \mathrm{d}P \cdot A_{\mathrm{M}} + \sqrt{\mu^2 \cdot R_{\mathrm{M}}^2 + 4 \cdot t_{15} \cdot \mathrm{MFI} \cdot \mathrm{d}P^2 \cdot A_{\mathrm{M}}^2}\right)} \tag{8}$$

where MFI is the measured MFI (l m$^{-6}$); $V_1$ is the volume of the first sample (m$^3$); $V_2$ is the volume of the second sample (m$^3$); $A_{\mathrm{M}}$ is the membrane area (m$^2$); $t_{15}$ is the elapsed filtration time 15 min (900 sec); d$P$ is the applied pressure (Pa); and μ is the water viscosity (Pa s).

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

## 3. Experimental

### 3.1. Membrane

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

### 3.2. Model water

α-Alumina hydrophilic particles (AKP-15, Sumitomo Chemical, Tokyo, Japan) were used with a core particle

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

| Code | Material | Nominal pore size (μm) |
|---|---|---|
| M1 | PVDF | 0.45 |
| M2 | PTFE | 0.45 |
| M3 | Acrylic polymer | 0.45 |
| M4 | Nitro cellulose[1] | 0.45 |
| M5 | Nylon6,6 | 0.45 |
| M6 | Cellulose acetate[1] | 0.45 |
| M7 | Cellulose acetate[1] | 0.45 |
| M8 | Polycarbonate | 0.45 |

[1]ASTM standard membrane material.

size of 0.6 μm and an isoelectric point (IEP) at pH 9 [12]. The AKP-15 is quite monodisperse particles due to particle size distribution curve. The feed solution was prepared with 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.

## 4. Results and discussion

The results of this work will be clustered in sections. SDI/MFI mathematical relation will be explained and verified. However, SDI/MFI relation is working properly if the dominated fouling mechanisms is pure cake filtration, the different 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 will be also studied. Finally, the equivalent MFI values for $SDI_{15}$ = 3 will be theoretically calculated.

### 4.1. 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 × $10^{-4}$ $m^2$, feed temperature 20°C, applied pressure (d$P$) 207 kPa. However, the relation SDI/MFI was plotted in Fig. 2 for various membrane resistances 0.25, 0.5, 1, 2, 4 and 8 × $10^{10}$ $m^{-1}$.

Increase the assumed MFI values leads to increase exponentially the calculated SDI value. Furthermore, the SDI/MFI relation influences by the membrane resistance. However, the relation between the membrane resistance and SDI is reverse proportional.

### 4.2. The influence of the particle concentration in the feed solution on SDI

MFI has a liner relation with particles concentration proved by Schippers and Verdouw [5]. Moreover, SDI has non-liner relation with the particles concentration. Fig. 3 shows the results of nine SDI test carried out at constant temperature 21.5°C and constant pressure (207 kPa) for three particle concentrations (AKP-15) 2, 4 and 8 ppm. Three SDI test for each concentration were

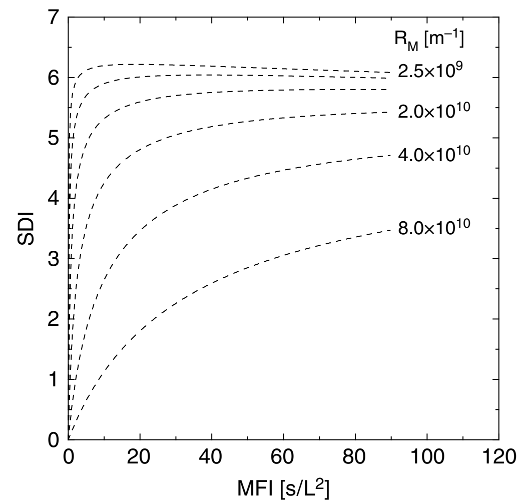


Fig. 2. The mathematical relation between SDI and MFI influenced by the membrane resistance (0.25 × $10^{10}$–8.0 × $10^{10}$ $m^{-1}$). Reference parameters were assumed: membrane area ($A_M$) 13.8 × $10^{-4}$ $m^2$, temperature 20°C and applied pressure (d$P$) 207 kPa.

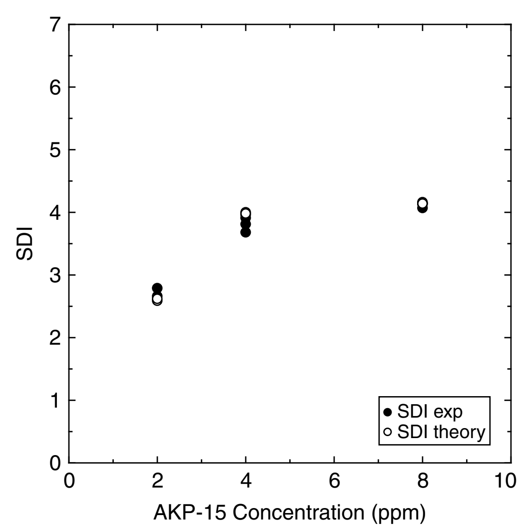


Fig. 3. Theoretical and experimental SDI results for different particle concentrations (2, 4 and 8 ppm). Feed solutions contained α-Alumina particles (AKP-15) with 0.6 μm size. The filtration experiments were carried out using cellulose acetate membranes M6.

carried out using the cellulose acetate membrane (M6) diameter 25 mm. The fouling mechanisms were verified as a cake filtration.

In Fig. 3, the experimental SDI results show a good agreement with the theoretical prediction of SDI using model 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 follow:

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

### *4.3. 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 α-Alumina particles (AKP-15) 4 ppm was prepared in big feed tank to remain a constant feed quality. SDI tests were carried at room temperature 21°C. The applied pressure remained constant 207 kPa. SDI results were plotted versus the membrane resistance in Fig. 4. 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

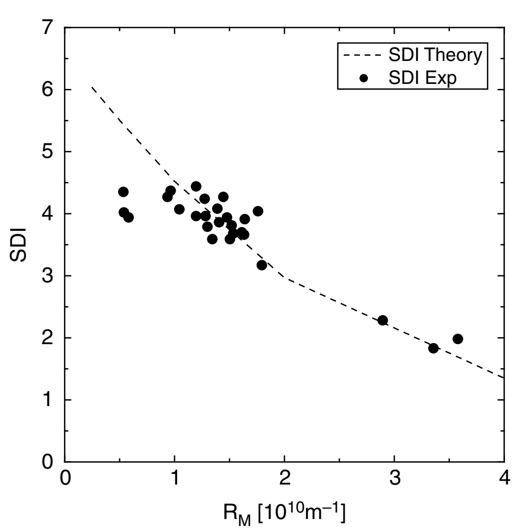


Fig. 4. SDI experimental and theoretical results for different membrane resistance materials and manufactures. The experiments carried out using particles concentration 4 ppm of AKP-15 under pressure 207 kPa.

theoretical SDI value for each experiment. However, the theoretical SDI values for various membrane resistances were estimated and plotted in Fig. 4.

Clearly, Fig. 4 shows the influence of the membrane resistance ($R_M$) on SDI. Both theoretical and experimental results show that SDI decreases with increase the membrane resistance ($R_M$). In other world, increase the membrane resistance from $0.5 \times 10^{10}$ to $3.5 \times 10^{10}$ m$^{-1}$ leads to decrease SDI results from 4.5 to 2 for the same water quality.

This great influence in the SDI result by the membrane resistance can be explained as follow:

For a constant particles concentration, the membrane with high resistance has low permeability. Consequently, the amount of particles that carried to the surface of the membrane with high membrane resistance will be less comparing with low membrane resistance. Regarding to the ASTM standard, SDI defined as the plugging rate per minute. However, for high membrane resistance, the plugging rate will be slower and SDI will be lower.

At constant pressure, Hagen–Poiseuille equation (Eq. (9)) and Darcy's low (Eq. (9)) were merged in one equation (Eq. (9)):

$$R_M = \frac{8 \cdot \mu \cdot \tau \cdot dx}{\varepsilon \times r^2} \tag{9}$$

where ε is the surface porosity; $r$ is the pore radius; μ is the water viscosity; τ is the tortuosity; and d$x$ is the membrane thickness.

From Eq. (9), the membrane resistance ($R_M$) can be described as a lump-sum of the membrane properties such as: pore size, porosity, tortuosity and membrane thickness. However, the membrane properties were varied regarding to the membrane material and manufactures, which explained the variation in the membrane resistance. The deviation between the theoretical results of SDI in and experimental Fig. 4 can be due to small particles can pass the membrane with low resistance. Besides that, the chance to start with pore blocking for longer time is high in the membrane with low resistance.

### *4.4. Normalizing and sensitivity study of SDI*

Regarding to the SDI list of disadvantages, SDI was not corrected for testing parameters such as membrane resistance ($R_M$), membrane area ($A_M$), feed temperature ($T$), and applied pressure (d$P$).

The mathematical bridge SDI/MFI in model 8 gives for the first time the opportunity to correct SDI. However, the membrane area ($A_M$) has no influence on SDI as far as the sample volumes were adjusted in direct proportion with the membrane area ($A_M$). Normalizing SDI needs to 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 (d$P$) 207 kPa

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

Further work on SDI normalizing and sensitivity will be reported in the following article.

## 5. Conclusions

Several disadvantages were reported, which makes SDI unreliable fouling test. However, 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 (d$P$).

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

As results of this study, Equivalent MFI values for $SDI_{15}$ = 3 were determined. However, equivalent MFI values were a function of membrane resistance used. Normalizing SDI for membrane resistance ($R_M$), feed temperature ($T$) and applied pressure (d$P$) is possible and will be in separated article.

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