New insights into silt density index and modified fouling index measurements

A. Nahrstedt and J. Camargo-Schmale

ABSTRACT

In order to investigate the accuracy and reproducibility of the parameters SDI (silt density index) and MFI (modified fouling index), tests in diverse conditions were performed: with three different types of filter holder, two microfilter pore sizes, with and without permeate spacer and with two foulants (alginate as organic foulant and silica flour as the particulate). Additionally the effect of pressure on fouling indices was analysed. It was concluded, that there is a need to define more boundary conditions in the ASTM standard (exact type of filter holder, exact type of membrane, start conditions) for the SDI to achieve a parameter with reliable and comparable values. But in comparison to MFI, SDI seems to be a more robust parameter for a use in practice pertaining to the influence of a feed pressure level and the effective membrane area. The MFI gives more insights in acting mechanisms and offers advantages for research. It shows a correlation to a concentration of particulate or organic foulants. Like the SDI, it is necessary to define and standardize exact boundary conditions for the MFI tests (classified by the use of MF, UF or NF filter media).

Key words | fouling, membrane filtration, modified fouling index (MFI), silt density index (SDI)

INTRODUCTION

Fouling is defined as the process resulting in loss of performance (permeability) of a membrane element. It is due to the deposition of suspended or dissolved substances, scaling and bacterial growth on external surfaces (membrane, spacer, etc.), at the membrane pore openings, and within its pores (Koros et al. 1996). Fouling increases the operational costs (energy demand, cleaning periods, membrane life-time, etc.). Thus, it is fundamental to have methods available to predict fouling. For the operating conditions of the membrane, the most important factor is the quality of the feed water, i.e. its fouling potential.

There are five mechanisms according to which particulate fouling of the membrane can be classified. Each of them builds up a specific resistance for the flux:

- mechanically blocking of membrane pores by colloids or molecules
- adsorption phenomena upon the membrane surface or inside the pores
- cake layer (gel layer) formation by retained particles, colloids and molecules on the membrane surface
- compression of the cake layer
- concentration polarization

Many studies have been done to achieve a parameter which predicts the fouling tendency of membranes, especially for RO and NF. The most common and acceptable tools are the Silt Density Index (SDI) and Modified Fouling Index (MFI). Both are based on the filtration of feed water through a 0.45 μm microfilter under a constant transmembrane pressure. They indicate the potential for particulate fouling of certain water. Other methods and parameters (suspended solids, particle counts, turbidity...) are also applied, but they are not accepted as reliable tools (Yiantsios et al. 2005).

Although SDI and MFI are widely used, they have several limitations. Both tests operate in dead-end flow (macroscopic view) while commercially RO and NF...
modules run in cross-flow mode. The effect of cross flow for the MFI has been covered by a model including the concept of deposition factor (Schippers et al. 1981). Thus, the shear effect present in cross-flow mode cannot be reproduced accurately. SDI is also criticised for being an empirical test, not based on any filtration theory (Lipp et al. 1990; Karabelas & Yiantsios 2002; Vrouwenvelder & van der Kooij 2003; Vrouwenvelder et al. 2003; Park et al. 2006).

Actually, Kremen & Tanner (1998) demonstrated that increases in the colloid concentration correspond to geometric increases in the SDI values. On the other hand, linearity of the MFI with foulant concentration has been demonstrated in various test cases. Though, the problem of inadequate coping of the membrane sheet with the effect of shear, membrane interactions and particles <0.45 μm still remains. Because the pore size of the filter is 0.45 μm, it is expected that such indices measure mainly the tendency of a membrane to be fouled due to particles. To deal with this problem, Schippers & Kostense (1980) developed the MFI_{0.05} (see also MFI_{UF}, Boerlage 2001; Boerlage et al. 2004), where ultrafiltration (UF) membranes are used, and Khirani et al. (2006) tried to use nanofiltration (NF) membranes for MFI_{NF} tests. However, additional research must be done for these new fouling indices with a higher values range to become established. There are still no recommended limits for a plant design established. Moreover long times and higher costs are required to perform the tests.

**Silt density index (SDI)**

The SDI test was developed by the DuPont Co. at the end of the 1970s. It is calculated from the rate of membrane plugging. Water is passed through a 0.45 μm membrane filter at constant applied pressure of 2070 hPa (30 psi, setup, see Figure 1). The time $t_i$ required for collecting the initial 500 ml of filtrate is measured. After $T = 15$ min of filtration, the time $t_f$ required for finally collecting 500 ml of filtrate is also measured. Plugging Factor PF and SDI are then calculated as follows:

$$\text{PF} = \left( \frac{V_i - V_f}{V_i} \right) \times 100\%$$

$$\text{SDI}_T = \frac{\text{PF}}{T} = \frac{1}{T} \left[ 1 - \frac{t_i}{t_f} \right] \times 100\% \text{ [%/min]}$$

The SDI is % flux decline per minute. In the case of PF > 75%, a successive second or third measurement should be carried out reducing the filter run time $T$ in steps of 5 minutes. The SDI procedure is standardized in ASTM D 4189–95 (2002). Undefined (but essential for the empirical nature of this test) are the exact types of filter holder and membrane.

**Modified fouling index (MFI)**

The MFI was developed in the early 1980s by Schippers & Verdouw (1980). It is derived from the SDI test procedure...
and from the Darcy equation with additive parameters for the flow resistance in case of cake filtration:

\[
\frac{1}{A} \cdot \frac{dV}{dt} = \frac{1}{\eta} \frac{\Delta p}{R_m + R_p + R_g}
\]

where \( V \) is the filtrate volume, \( t \) the time, \( \eta \) the water dynamic viscosity, \( \Delta p \) the pressure drop across the filter, including its deposits and \( A \) the membrane area. The total resistance acting on the fluid flow is given as a sum of the resistances: \( R_m \) for the clean membrane, \( R_p \) due to pore blocking and \( R_g \) for the growing cake:

\[
R_g = \alpha c \cdot \frac{V}{A} = \frac{IV}{A}
\]

\( \alpha \) is defined as the specific cake resistance per unit weight, and \( c \) as the mass concentration of particles, combined to a measure of the fouling potential \( I \) of a certain water. Now, considering that no compression of the cake occurs, and integrating at constant \( \Delta p \), yields:

\[
\frac{t}{V} = \frac{\eta(R_m + R_p)}{A \cdot \Delta p} + \frac{\eta I V}{2 \cdot \Delta p \cdot A^2}
\]

The MFI is then defined as the slope of the linear dependency of \( t/V \) on the volume \( V \), and on the basis of the empirical standard for the boundary conditions (dynamic viscosity \( \eta_{20} \) at 20°C and pressure \( p_{2100} = 2,100 \text{hPa} \)):

\[
\text{MFI} = \frac{\eta I}{2 \cdot \Delta p \cdot A^2}; \quad [s/l^2]
\]

The setup of the MFI test is the same as that used for SDI. The volume of filtrate is measured every 30 seconds or continuously for 15 minutes. Quantity \( t/V \), the inverse of the flow rate, is then plotted against the volume (Figure 2), and the slope of the linear part of the curve \( \tan(\beta) \) is calculated and corrected to MFI for the standardized

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Pros and cons of the tests SDI and MFI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td><strong>Cons</strong></td>
</tr>
<tr>
<td>SDI</td>
<td>Simple</td>
</tr>
<tr>
<td>Standardized</td>
<td>Empirical</td>
</tr>
<tr>
<td>Can be performed <em>in situ</em></td>
<td>No linear relationship with the amount of foulant</td>
</tr>
<tr>
<td>Established</td>
<td>High permeation rate comparing with RO membranes</td>
</tr>
<tr>
<td>MFI</td>
<td>Linear relationship with foulant</td>
</tr>
<tr>
<td>Based on cake filtration theory</td>
<td>Standardization incomplete</td>
</tr>
<tr>
<td>Different fouling mechanisms can be observed</td>
<td>More complex and more expensive than SDI</td>
</tr>
<tr>
<td>Broader value range than SDI</td>
<td>(equipment and calculations)</td>
</tr>
<tr>
<td>SDI and MFI</td>
<td>Only dead-end operation mode</td>
</tr>
<tr>
<td>Fouling potential of particles &lt; 0.45 μm not considered with SDI and MFI&lt;sub&gt;0.45&lt;/sub&gt;</td>
<td>Insufficient accuracy and precision</td>
</tr>
</tbody>
</table>
pressure and temperature:

\[
\text{MFI} = \frac{\eta_2}{\eta} \frac{\Delta p}{D_{\text{p}2100}} \tan \beta
\]

The pros and cons of SDI and MFI are compared in Table 1.

**MATERIAL AND METHODS**

To obtain standardized water with a low fouling potential, a loop system was built: Tap water was pre-filtered by MF (0.2 μm Sartobran P, Sartorius), and stored in a 20 L glass recipient. In the loop it was pumped to an activated carbon filter and further to an UF membrane (0.01 μm, Membrana) and back to the glass recipient. Turbidity was continuously measured (Filter Trak 660sc, Hach Lange) reaching values below 14 mFNU.

Silica grain SF 600 (Sikron, Westdeutsche Quarzwerke, \( \rho = 2.65 \text{ g/cm}^3 \)) was used as model foulant for particulate fouling experiments with a particle size range of 2 – 12 μm. As model for organic foulant (without biofouling), polysaccharides, i.e. sodium alginate (sodium alginic acid, Sigma Aldrich) were used in different concentrations (0.01 – 2 mg/l). Further experiments mixing both foulants were conducted: 1 mg/l SF 600 and 0.02 mg/l alginate. The feed water temperature of all experiments was kept at 20.5°C.

Three different filter holders were tested, shown in Figure 3:
- Millipore Inline XX43 047 00, Ø 47 mm (M1)
- Sartorius SM 16 249, Ø 47 mm (S1)
- Sartorius SM 16 223, Ø 25 mm (S2)

Both Sartorius filter holders are made of stainless steel and differ only in their dimensions. S1 has a long body with 200 ml capacity, S2 only 20 ml. The membranes are supported with two PTFE-coated screens. The Millipore filter holder body M1 is made of polypropylene. Contrary to S1 and S2, it has a flat body with a narrow entrance for the flux, which spreads into a lamellar distribution system.

As the nominal membrane area of S2 differs from those recommended for the SDI and MFI (Schippers & Verdouw 1980), some adjustments to the formulas for SDI and MFI were necessary. The volumes collected at \( t_i \) and \( t_f \) for the SDI measurement, were reduced proportionally to the fraction of membrane area; instead 500 ml, 113.4 ml were collected. And the MFI was also corrected by the ratio of both membrane areas:

\[
\text{MFI}_{S2} = \frac{113.4}{500} \cdot \frac{25}{46} \cdot \text{MFI}
\]

Membranes with two pore sizes were used: 0.45 μm pore size, as recommended by ASTM D 4189 – 95 (2002) and 0.22 μm (both Millipore, mixed cellulose esters).
RESULTS

Influence of the filter holder

SDI and MFI for standardized pure water were measured employing all three filter holders in five repeated tests for each. The behaviour of the normalized flux $J/J_0$ for tests with a minimum SDI are shown in Figure 4. M1 had the lowest value for SDI and also very low and constant flux decline. Comparing S1 and S2, in the first minutes S1 had a stronger but later a smaller decrease in the flux than S2. As shown, on the basis of extrapolation of the measured data, it is important to neglect the initially occurring oscillation of pressure and start to collect the initial 500 ml volume immediately. All the results are summarized in Table 2.

The mean SDI value measured with filter holder M1 was much lower than with S1 and S2 (0.9%/min against 2.0 and 2.6%/min); its relative standard deviation a little higher (10%, versus 8% and 5%, respectively). The SDI values of S2 showed fewer variations than the other two. But its minimum SDI value was 2.5%/min. S1 also produced very high SDI values for such purified water (minimum 1.8%/min).

Looking at the much more scattering results for MFI in Table 2, it can be seen that the most stable of them was S1,

<table>
<thead>
<tr>
<th>Filter Holder</th>
<th>SDI [%/min]</th>
<th>MFI [s/l²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sartorius S2</td>
<td>2.5 2.9 2.64</td>
<td>0.8 0.9 0.90</td>
</tr>
<tr>
<td>Sartorius S1</td>
<td>1.8 2.2 2.04</td>
<td>0.19 0.29 0.22 11.4%</td>
</tr>
<tr>
<td>Millipore M1</td>
<td>0.8 1.2 0.90</td>
<td>0.41 0.73 0.41 36.8%</td>
</tr>
</tbody>
</table>

M1 SDI = 0.8
S1 SDI = 1.8
S2 SDI = 2.5

Contrary to filter holder S1, M1 has a narrow inlet and a flat lamellar divided body. This enforces cross flow effects on the membrane (based on geometry, roughly estimated cross flow velocity of 0.1–0.4 m/s) as visualized with black particles (ink) retained on the membrane: it could be observed that in the centre and in the borders there was a strong deposition of ink particles at stagnation points with higher pressure and permeation through the membrane. The flow is distributed from the centre to the border of the filter by 8 separate channels. The flow through each seam produces stronger shear forces in the middle. (See grey zones with thinner cakes in Figure 5).

In addition, the MF membranes showed a strong engraving after the experiments due to a supporting system of grids or bars. In consequence, the active membrane areas of all filter holders are smaller than the area in contact with the liquid because of the sealing effects of the supporting system (white lines in Figure 5 for M1 or point grit for S1 and S2). Paulus (1995) suggested to utilize a permeate spacer between the filter and its base to minimize this effect. He reported a reduction of 58% for the SDI and 75% for the MFI values.

Therefore, a 100 µm nylon sieve cloth (Scrynel NY 100 HD) was employed as additional base in S1 to increase the
active membrane (closer to the value of the calculated nominal area $A_{\text{nom}}$). Experiments were performed with several kinds of feed water (Table 3).

An observed flux rise resulted not only in an increase on the total volume required to calculate the indices, but also in a decrease of 30–40% in the mean time necessary to collect 500 ml for the SDI. An influence on the resulting SDI values could not be observed (either the same value or 0.1 units lower). The use of a spacer had no influence on the SDI values, but the MFI showed a decrease of 50–80%. This was expected since the thickness of the cake formed with the proceeding volume and therefore the resistance as well as tan($\beta$) is lower.

Influence of the pressure applied

The influence of feed pressure on the results for fouling indices was analysed varying it from 500 up to 2,100 hPa (Table 4). The calculation of the MFI includes a correction factor for pressure to a reference pressure of 2,100 hPa, and therefore it should be independent of pressure. The pressure for SDI measurements is fixed by the ASTM standard to 2,070 hPa. It was surprisingly verified that when the pressure was below the prescribed limit of 2,070 hPa, it didn’t affect the SDI values. This is because the SDI is an index that only compares the drop in the flow. The ratio of the flux at the beginning and at the end ($T$) of the measurement might be similar for different experiments with different applied pressures.

Contrary to the theory, the MFI was sensitive to pressure changes and varied inversely proportionally to the applied pressure. Other reports from Schippers et al. (1981) and his co-workers (Boerlage et al. 1998), showed results that were also pressure dependent. In most cases the MFI varied proportionally to the applied pressure as a result of the compressibility of the cake formed. Schippers introduced an empirical compressibility coefficient to calculate the MFI.

Influence of different foulants

SF 600 silica flour (1 mg/l) was tested as a typical particulate foulant found very often in natural waters using filter holders S1 and M1 (Table 5). Similar to the results for standardized pure water, the values obtained here were lower for M1 than for S1, but again with a higher relative standard deviation of the SDI. Comparing the test with and without silica flour, there is an increase of SDI and MFI values depending on the flow resistance of an uncompressed cake.

Alginate was added as the organic foulant. Many researchers have suggested humic acid as the most detrimental Natural Organic Matter (NOM) foulant, but recent studies have shown that polysaccharides and proteins might be a more considerable foulant, at least regarding UF, NF and also in RO membranes. With initial concentrations of 2 mg/l down to 0.1 mg/l, a strong flux decline occurred and the SDI$_{15\text{min}}$ was maximal (6.6 and 6.55%/min, see Figure 6). The concentration was then reduced to 0.02 and 0.01 mg/l and lower results were achieved (SDI = 3.9%/min and 3.3%/min respectively).
In Figures 6 and 7, the effect of alginate concentration variation on the SDI and MFI curve is illustrated. The strong increase in the slope of $t/V$ versus $V$ for concentrations above 0.1 mg/l might be due to compression of the cake or gel layer formed by the alginate. But ($\beta$) has to be calculated as the slope of the curve before cake compression takes place. Now, comparing the SDI and MFI for each type of feed water, it can be seen that both values decrease with decreasing concentration of foulants (Table 6).

Although the SDI is a parameter that measures mainly particulate fouling, it was proved that organic foulants can also produce high SDI values. One of the main fouling mechanisms for organic foulants is adsorption. Microscopic analyses of the filter pad employed to test a 0.02 mg/l alginate solution were carried out in order to observe the cake and discover the mechanism of fouling formation. A confocal laser scanning microscope (Zeiss LSM 510) was used. The filter pad was immersed in a fluorescent solution of lectin concanavalin-A (Con-A) to colour the alginate. Figures 8 and 9 show the cake layer formed on the filter surface.

In Figure 8, a lateral view of the cake is shown. The cake layer had a thickness of approximately 35 $\mu$m. At the top of the layer the concentration of alginate is more intense than near the membrane, and at some points alginate penetrates the membrane pores, proving that adsorption occurred. The alginate agglomerated and built up bigger structures that

<table>
<thead>
<tr>
<th>Filter Holder</th>
<th>Turbidity [FNU]</th>
<th>SDI [%/min]</th>
<th>MFI [s/l²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sartorius S1 $\varnothing = 47$ mm</td>
<td>0.68</td>
<td>4.2</td>
<td>4.4</td>
</tr>
<tr>
<td>Millipore M1 $\varnothing = 47$ mm</td>
<td>0.65</td>
<td>3.0</td>
<td>3.3</td>
</tr>
</tbody>
</table>

$\beta = 75\%$.

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![Figure 6](image1.png)  
Figure 6 | Effect of different alginate concentrations on the SDI using filter holder S1.

![Figure 7](image2.png)  
Figure 7 | Effect of different alginate concentrations on the MFI using filter holder S1 (2 mg/l alginate correspond to 0.8 mg/l TOC).

![Figure 8](image3.png)  
Figure 8 | Alginate cake on the filter surface, 1,000 £ magnified, (a) lateral (0 £ membrane surface, 35 £ top of the cake) and (b) upper view.
were easily retained by the filter so that cake formation takes place. Figure 9 shows that only a smaller concentration of alginate reached the filter pad, most of it was trapped by alginate agglomerations at the cake.

When both foulants were added together (0.02 mg/l alginate and 1 mg/l SF600), the influence on both fouling indices is very different, as shown in Table 7. While the SDI with almost constant values had a relatively small increase with the additional alginate (from 4.4%/min for pure SF600 up to 5.35%/min, calculated as SDI15), the MFI calculated was very inconstant, with results from 2.3 up to 7.5/l² and a variation of almost 50% (8.6%/min for pure SF600).

On the other hand, for this test and the chosen pressure there is only a small linear part of the curve t/V versus V characterizing a phase with pure cake filtration. It went from blocking filtration very fast to cake compression, and a compressibility correlation should be added to the MFI formula to obtain more accurate values.

The influence of foulants on increasing fouling indices was more visible with the addition of organic foulants to the feed water. A very small concentration produced high indices (Table 7). It can also be seen that alginate and silica flour, when added together to the standard water, produced lower fouling indices than the sum of their fouling index experiments separately, which could be expected for the MFI. The organic foulant adsorbs primarily onto the surface of particles accumulated on the membrane surface, and therefore their adsorption on and/or within the membrane pores were drastically reduced (Park et al. 2006).

### Measurements with filtrate

The filtrate of some previous tests was stored and tested again. The experiments were performed utilizing the filter holder S1 (incl. spacer). When silica SF 600 was added as foulant alone in the first test, the SDI for the filtrate was still high (>3.0%/min, Table 8). This may have been due to the

#### Table 8 | Turbidity, pH and fouling indices for different feed water and for their retested filtrates in comparison to standardized pure water (SW)

<table>
<thead>
<tr>
<th>Feed water</th>
<th>Turbidity [FNU]</th>
<th>SDI [%/min]</th>
<th>MFI [s/l²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW + SF 600 (1 mg/l)</td>
<td>0.78</td>
<td>5.1</td>
<td>4.075</td>
</tr>
<tr>
<td>Its first filtrate</td>
<td>&lt;0.03</td>
<td>3.7</td>
<td>1.005</td>
</tr>
<tr>
<td>Its second filtrate</td>
<td>&lt;0.03</td>
<td>3.1</td>
<td>0.64</td>
</tr>
<tr>
<td>SW + Alginate (0.02 mg/l)</td>
<td>&lt;0.03</td>
<td>4.3</td>
<td>1.056</td>
</tr>
<tr>
<td>Its first filtrate</td>
<td>&lt;0.03</td>
<td>2.5</td>
<td>0.209</td>
</tr>
<tr>
<td>Its second filtrate</td>
<td>&lt;0.03</td>
<td>2.2</td>
<td>0.143</td>
</tr>
<tr>
<td>SW + Alginate + SF600</td>
<td>0.63</td>
<td>5.2</td>
<td>2.515</td>
</tr>
<tr>
<td>Its first filtrate</td>
<td>0.07</td>
<td>3.1</td>
<td>0.818</td>
</tr>
<tr>
<td>SW (direct)</td>
<td>&lt;0.03</td>
<td>2.0</td>
<td>0.227</td>
</tr>
</tbody>
</table>
high amount of grains with a smaller diameter than the pore size of the membrane. Some grains that passed through pores in the first filtration were retained in the second test.

It was supposed that for the experiments using alginate, the SDI of the filtrate would be almost the same as the original feed water, once adsorption was expected to be the main retention mechanism. Nevertheless, even the first filtrate had a relatively low SDI comparable to the values calculated for the standard water (Table 8). So although adsorption occurred, the main retention mechanism was cake filtration.

Analysing the results in relation to turbidity, it can be seen that it is a poor method for measuring fouling potential of waters, as it showed a good relationship with the other two indices (SDI and MFI) only when silica was used as foulant. As soon as organic foulant was added to the water, the turbidity had no variation, but the results for SDI, MFI and flux decline strongly increased.

**CONCLUSION AND RECOMMENDATIONS**

The parameters SDI and MFI were studied, to determine and to classify the influence of external factors on the test procedure, the calculation and the result of such indices. Four factors were analysed: filter holder type (i), feed pressure (ii), microfilter pore size (iii) and additional support spacer (iv) for the 47 mm long body filter holder from Sartorius.

It was verified that the filter holder employed had a very strong influence on the SDI values obtained. A difference of more than 100% was measured in the SDI calculated for the same feed water using the 47 mm in-line filter holder from Millipore (M1) (mean SDI ca. 0.9%/min) from the results calculated using the 47 mm filter holder from Sartorius (S1) (2.0%/min) and the 22 mm filter holder Sartorius (S2) (2.6%/min). The values obtained with S2 were the most stable of them, with only 5% variation but it produced also very high SDI values (ca. 2%/min). The flow behaviour in the filter holders M1 and S1 were also studied. By adding ink to the feed water and observing its patterns on the membrane, it could be verified that the flow through M1 is operating partially in cross-flow mode with an acting shear stress for the membrane filter or its deposits. This suggested that the low values obtained with the filter holder M1 were underestimated, since pores that were blocked or layers that were formed may become free as particles already settled on the filter are lifted and moved due to cross-flow effects. However, for the MFI results, the difference between filter holders wasn’t so pronounced. While for the SDI the difference was above 90% between S1 and M1, it was no more than 20% for the MFI.

Comparing the positive and negative effects of the filter holders S1 with M1:

- **S1**: + homogeneous flow field in the holder and constant flow through the filter pad
  - very narrow range for SDI values, since its minimum was 1.8%/min
- **M1**: + broad range for SDI values
  - shear gradients acting on parts of the membrane surface

The influence of the feed pressure on the results for fouling indices was analysed, varying it from 500 till 2,100 hPa. Theoretically, MFI results should be independent of pressure, because they include a model based correction factor for pressure, whereas SDI requires a defined pressure of 2,070 hPa (30 psi). Despite this, the results of the tests with different applied feed pressure showed that the influence of pressure on the SDI values could be neglected if they were below the recommended value. Contrary to the theory, pressure presented a strong influence on the MFI values. The probable explanation for this is that the cake formed on the filter surface was compressible and therefore a compressibility factor should be applied to calculate the value with more accuracy.

It was expected that filters with smaller pores would produce higher SDI, since they could retain also particles with smaller diameter. Nevertheless, the SDI results obtained with filters with a pore size of 0.22 μm (SDI = 1.4%/min) were lower than the ones measured with the standard filters of 0.45 μm (SDI = 2.1%/min). This may be related to the slower flow velocities through the filter and pores, produced by the small pore diameter: if less volume flows through the filter, the accumulation of particles is slower, and consequently the SDI value becomes lower.

The utilization of an additional support–spacer, on the filter holder S1, brought more disadvantages than advan-
tages, especially regarding the SDI. It had no significant effect on the SDI values, but it increased the active membrane area and consequently increased the flow though the filter and the amount of water necessary to measure the fouling indices. This produced a reduction of 30–40% in the mean time necessary to collect the 500 ml for the SDI calculation. This time reduction augmented the systematic error for the SDI. On the other hand, a reduction of more than 50% on the MFI values was achieved using a spacer.

The SDI shows several deficiencies. Well known is the fact that it has no linear relation with the concentration of suspended and colloidal matter. From this study it becomes clear that the accuracy and reproducibility (precision) are not high, probably also due to variations in membrane properties. In addition, the use of different filter holders resulted in large differences in SDI values. This recommended an exact specification of a better quality membrane as well as the specification of a defined filter holder. None of the filter holders studied showed satisfactory results to be classified as the ideal filter holder to perform the tests. M1 produced shear stress on the filter cake, which could mask the real SDI and MFI values; S1 and S2 had minimum values of 1.8%/min and 2.4%/min respectively, which are too high. Other filter holder types should be tested to find a suitable one to be used as standard. The conditions for the start of the test (start of the filtration and time measurement) have a great influence on the accuracy of the SDI and should also be stated more precisely in the standard.

To reduce the systematic error of low fouling waters, 1,000 ml instead of 500 ml should be collected. And in order to determine the fouling index of water with high content of dissolved solids (SDI > 5%/min) a new measure, SDI<sub>PF=75%</sub>, was suggested by Mosset et al. (2008), where the SDI is calculated with the measured filtration time T necessary to reach exactly PF = 75% plugging, and not with T = 15,10 or 5 min. Fixing the absolute percentage of plugging produces more uniform and reproducible values and provides a parameter with a continuous value range.

MFI has some advantages against SDI. It considers variations in the flow, has no maximal limit value (like SDI) and has a stronger theoretical justification. In experiments with a repeated reuse of filtrate from previous SDI and MFI tests there was only a small drop in the SDI values, whereas the decrease in MFI values indicates properly the proceeding loss of particulate and organic foulants. However, it is also an index with several deficiencies. It is not standardized. In general and particular in the case of a higher amount of organic foulants in the feed water, the MFI values of our tests showed a very low reproducibility. The MFI is pressure dependent. To compensate the pressure dependency, a factor for the cake compressibility can be added to the MFI model and formulas (Boerlage 2000). But in common practical applications its value is not known and its determination is time consuming. To predict UF, NF or RO fouling, MFI<sub>UF</sub> should be used. Up to now, important boundary conditions for the MFI are not standardized. Therefore, MFI value ranges of different labs or research teams are not comparable.

**REFERENCES**

ASTM 2002 Standard test method for silt density index (SDI) of water. D 4189–95


