Why MFI is edging SDI as a fouling index

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Editor’s Note: The fouling potential for reverse osmosis and other membrane systems has been a hot topic for many years. D&WR has published several articles comparing the Silt Density Index with the newer Modified Fouling Index. As it is becoming apparent that the latter system of measurement is about to become the preferred method, this article looks at why this is happening.

PARTICULATE FOULING has plagued reverse osmosis (RO) systems since their first use in desalination and remains a persistent issue today for RO and other pressure-driven systems such as microfiltration (MF), ultrafiltration (UF) and nanofiltration (NF). In the early 1960s, the Du Pont Company/Permasep Product successfully launched the hollow-fine-fibre (HFF) permeator onto the desalination market, where it dominated for several decades.

A well-known weakness of this permeator was its vulnerability to fouling. Initially, this vulnerability was attributed to suspended and colloidal matter in the feed water, i.e., particulate fouling. Therefore, Du Pont developed the Silt Density Index (SDI), initially named the Fouling Index, as a parameter to characterize the fouling potential of the feedwater for permeators.

The fouling mechanism turned out to be more complicated than just fouling of the membrane surface as initially assumed. Gradually it became clear that the fouling was initiated by local clogging of the woven or non-woven fabric between the fibres, which is needed to ensure equal flow distribution of the feed water (see Figure 1).

This primary fouling mechanism disturbs the flow pattern resulting in localised low flow, causing high concentration polarization and higher recovery rates in that area. This then leads to higher osmotic pressure, deposition of suspended and colloidal particles and scaling, for example, of calcium sulphate, reducing the permeate flow.

In the 1980s, it became clear that biofouling also frequently occurred, resulting in the same phenomena and exacerbated fouling. The synergistic effects of these fouling types made the fouling problem even more complicated.

In the 1990s, spiral-wound elements were gaining ground in the market, claiming to be less vulnerable to fouling, which was reflected in their less stringent SDI guidelines, i.e., a maximum SDI of 5 was allowed in membrane guarantees, with an SDI of <3 preferred. SDI guidelines for Permasep permeators were SDI <3 and preferably SDI of <1.

Spiral-wound elements were indeed less vulnerable to clogging than the HFF permeators, attributable to differences in design and wide spacing between spacer and membrane surface. The same holds for the HFF element used today, having cross-wound fibres with wide spacing between these fibres.

While the SDI is a useful tool in characterizing the particulate fouling potential of RO feed water, when it comes to clogging of fabric in permeators, spacers in spiral-wound elements and the new type of HFF elements, it may not account for the direct fouling of the membrane surface itself, which results in a permeability decline. This raises the question: Is the SDI a useful tool in predicting this type of fouling as well? This paper examines this question and traces the development of the SDI and the more recent Modified Fouling Index (MFI).

SILT DENSITY INDEX

The SDI, standardized by ASTM, is based on filtration of feed water through a 0.45 µm membrane in dead-end mode at constant pressure (207 kPa). The rate of
plugging is measured and expressed as % flux decline per minute. As the SDI is simple to perform and cheap, it has been universally applied for the last 50 years as a tool to assess the particulate fouling tendency of a feedwater, the effectiveness of pretreatment processes etc, and is often the basis of membrane guarantees and other plant performance contracts.

However, increasingly, the value of this test to predict the rate of fouling in RO systems due to particle deposition is being questioned. The limitations of the SDI test are well documented and include 2–6:

• No correction for test water temperature
• Result heavily dependent on the test membrane permeability
• Not applicable for testing high-fouling feedwater, e.g., raw water – ASTM recommends that turbidity should be <1 NTU
• Not applicable for testing UF permeate, which is increasingly being used in desalination pretreatment
• No linear relation with colloidal/suspended matter
• Fouling potential of particles smaller than 0.45 µm not measured
• Not based on any filtration mechanism.

The absence of temperature correction results in higher SDI values at higher temperatures. Additionally, the non-linear relation between the measured SDI value with particle concentration means that water appears less fouling than it is, as the test filter becomes progressively plugged.

This is demonstrated in Figure 2 for SDI measurements after 5, 10, and 15 minutes filtration for a formazine solution.

The net result is that SDI cannot be directly compared when measured at different temperatures or for different filtration intervals and for more fouling conditions.

Theoretical prediction of flux decline in RO systems based on SDI results in extremely high fouling rates, e.g., SDI = 3, effectively means a flux decline of 3% per minute. Applying a direct correction between the SDI test flux (>1,600 L/m²h at the start) to a typical RO flux (about 20 L/m²h), predicts a flux decline of 20% per hour. This rate of fouling is far outside the rates observed in practice.

To overcome these deficiencies, the Modified Fouling Index (MFI) using the same 0.45 µm membrane filters (MFI-0.45) and MFI using ultrafiltration membranes and performed at constant flux (MFI-UF) were developed.

**MODIFIED FOULING INDEX (MFI-0.45)**

The MFI-0.45 test uses the same equipment as the SDI test. It takes into account that, initially, pore blocking occurs, followed by cake/gel filtration and, finally, cake/gel blocking and/or enhanced compression.

The MFI value is determined from the stage of cake/gel filtration and is defined as the minimum slope (tg α) in the curve t/V versus V. Where t = total filtration time, and V = total filtered volume (see Figure 3).

\[ MFI = \frac{n t}{2 A P} \]

Where: \( \Delta P \) = net driving pressure (N/m²); \( n \) = viscosity (N·s/m²); \( l \) = fouling potential (m³); \( A \) = surface area of membrane filter (m²)

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Figure 2: SDI as function of formazine concentration and filtration time

Figure 4: Relation between MFI and formazine concentration

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The obtained MFI value is corrected for temperature and pressure and shows a linear relation with colloidal/suspended matter concentration (Figure 4).

Predicting the rate of fouling in RO systems based on the MFI-0.45 is possible, assuming that cake/gel filtration is the dominant mechanism. However, the predicted rate of fouling turns out to be very low for an MFI of 1 s/L², (equivalent to SDI15 1 to 3). A pressure increase of 1 bar is predicted to occur in more than 100 years with RO feedwater with an MFI-0.45 = 1 s/L². This calculation is based upon equation 2 (see 9-11 for its derivation).

\[ \Delta P = \eta \cdot R_m \cdot f + \eta \cdot I \cdot f^2 \cdot t \]

Where: \( \Delta P \) = net driving pressure (N/m²); \( \eta \) = viscosity (N-s/m²); \( R_m \) = membrane resistance (m²); \( f = \) fouling potential derived from MFI (m²); \( I = \) flux (m³/m²·s); \( t = \) time (s)

**MODIFIED FOULING INDEX – ULTRAFILTRATION (MFI-UF)**

Based on the above, it was concluded that particles much smaller than 0.45 µm were...
responsible for the fouling rate observed in practice. This was supported by the measurement of MFI with membranes of different pore sizes varying from 0.8 µm down to 0.05 µm for RO feedwater, which resulted in respective MFI values increasing from 4 to 4,500 s/L².

Consequently, the MFI-UF test with UF membranes was developed to capture these smaller particles. Brackish water measurements with the MFI-UF test using 13 kDa molecular weight cut off (MWCO) UF membranes (see Figure 5) demonstrated that the cake/gel formed on the membrane surface was quite compressible (see Figure 6).

Due to this compressibility, accurate prediction of fouling in RO was not possible using the new MFI-UF test in constant pressure mode. Hence, the MFI-UF test was developed in constant flux mode, whereby pressure increase to maintain constant flux over time is recorded. The fouling potential I is derived, from the slope in equation 2, and converted into MFI (Equation 1).

The MFI-UF constant flux equipment uses flat 25 mm diameter UF membranes (see Figure 7). Filtration flux can range between 10 L/m²h to 300 L/m²h.

Water from the North Sea tested with 10 kDa and 100 kDa membranes showed rather high MFI and a remarkably strong dependency on flux. 10 kDa membranes gave MFI values 4-5 times higher than 100 kDa, which clearly indicate that small particles dominate the fouling potential (Figure 8).

The dependency of MFI on flux, means that to accurately predict particulate fouling in RO systems, the MFI should be measured at a flux similar to a RO system (close to 20 L/m²h) or extrapolated from higher fluxes.

**PREDICTING PRESSURE INCREASE IN RO SYSTEMS**

Generally, RO desalination plants operate at constant flux to meet production requirements. Changes in feedwater temperature are compensated for by adjusting feed pressure.

Similarly, fouling resulting in an increase in membrane resistance is compensated for by increasing the feed pressure and hence net driving pressure (NDP). In this case, increase in the NDP can be predicted through equation 2. However, for accurate prediction a correction factor, deposition factor $\Omega$ has to be incorporated. $\Omega$ takes into account that not all particles passing the membrane surface (in cross flow) deposit and remain attached.

Note: Osmotic pressure enhanced fouling is not accounted for in this equation. Consequently the pressure development might be under-predicted.

Based on equation 3, a theoretical “safe MFI” can be calculated, assuming, $\gamma$, an allowable increase in NDP of 1 bar in 6 months. Figure 10 illustrates MFI calculated as a function of the deposition factor $\Omega$ at a flux of 10 to 20 L/m²h, which is commonly applied in seawater RO.

“Safe MFI” values are heavily dependent on the deposition factor, emphasizing the need to determine deposition factors in full scale and pilot plants.

An indication of the deposition factor can be obtained by measuring the MFIfeed in feed water and MFIconc in the concentrate and applying equation 4, which is based on a balance for MFI:

$$\Omega = \frac{1}{R} + \frac{\text{MFI}_{\text{conc}}}{\text{MFI}_{\text{feed}}} \cdot \left(1 - \frac{1}{R}\right)$$

Where: $R$ = recovery (–)
Deposition factors determined with MFI-UF using test membranes varying between 100 and 5 kDa for feedwater (pretreated with UF) at a seawater RO pilot plant in Jacobahaven (the Netherlands) showed $\Omega$ ranged between 0.20 to 0.45 (see table 1).

<table>
<thead>
<tr>
<th>Membrane, MWCO</th>
<th>100 kDa</th>
<th>50 kDa</th>
<th>10 kDa</th>
<th>5 kDa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deposition factor $\Omega$</td>
<td>0.23</td>
<td>0.29</td>
<td>0.20</td>
<td>0.45</td>
</tr>
</tbody>
</table>

The performance of pretreatment processes at the Jacobahaven SWRO demonstration plant was assessed using MFI-UF measured with 100, 50 and 10 kDa test membranes as shown in Figure 10. The Amiad strainer showed only a small reduction in MFI-UF, as expected, with a relatively large aperture size of 50 µm. Whereas, the reduction in MFI-UF (and fouling) observed following UF (nominal MWCO of 150 kDa) was much larger, $\eta_f$, of 94%, 93% and 88% reduction for 100 kDa, 50 kDa and 10 kDa MFI-UF test membranes, respectively. These results clearly illustrate that the MFI-UF can be used (at any temperature) to measure low and high fouling feedwater and for UF permeates.

FOULING POTENTIAL IN UF AND MF SYSTEMS

Predicting the rate of fouling in MF and UF systems, $\eta_f$, development of pressure during operation at constant flux, seems to be less complicated than in RO systems, since filtration is conducted in dead-end mode. Hence, the deposition factor $\Omega$ is 1.0, completely eliminating the need to measure $\Omega$.

Moreover, the MFI can be measured using the same membrane as applied in the full scale plant, so that Equation 2 can be applied to predict the development of the pressure during one cycle. Recently transparent exopolymer particles (TEP) have been identified as potential foulants in MF, UF and RO. These foulants, originating from algal activities and other aquatic life, have been overlooked by the industry for many decades. Villacorte 14 recently developed a method to semi-quantitatively measure the concentrations of TEP down to a size of 10 kDa. A good correlation was observed between TEP10 kDa and MFI-UF measured with membranes having pores of 10 kDa at a constant flux of 60 L/m²h.

The data shown in Figure 11 originate from 5 different plant locations including lake, river and seawater.

CONCLUSIONS AND RECOMMENDATIONS

The presented results illustrate the benefit of the MFI-0.45 test to the industry to determine the particulate fouling potential of both high and low fouling feedwater. The MFI is corrected for temperature and pressure and has a linear relation with suspended/colloidal matter. Semi- and fully automated equipment is available on the market to simultaneously measure MFI-0.45 and SDI on-line.

The observed deficiencies in the SDI test and the demonstrated advantages of MFI have led the ASTM Committee charged with recertifying SDI to revisit the protocol for SDI and to start the approval process for a second standard based on the MFI test method.

MFI-UF provides insight into the fouling potential of a feedwater due to particles smaller than 0.45 µm and enables one to measure the effect of different pretreatment processes on these particles. Three major aspects need to be addressed in further developing the MFI test:

- MFI test membranes with even smaller pores, ideally close to the nanofiltration range, and preferably down to 5, 1, and 0.5 kDa. Unfortunately, membranes, in flat sheet form, and having sufficient permeability are not yet available on the market. Consequently, pencil capillary membranes modules need to be applied, complicating further research and application.
- Measuring the deposition factor $\Omega$ in a multitude of full-scale plants to define the “safe MFI”. This requires operational data on fouling rates in RO systems. Differentiation between particulate fouling and biofouling is also required.
- Measuring the enhanced osmotic pressure effect due to fouling in full-scale plants.

International collaboration of research organizations and the industry worldwide is proposed in order to establish a database of operational data and MFI-UF measurements for a wide range of RO feed water, pretreatment options and operational regimes. Such a database would be of considerable value to process engineers and plant operators in designing and operating desalination plants.

References