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SDI normalization and alternatives

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A B S T R A C T

Estimating the fouling potential is a prerequisite for controlling membrane fouling in reverse osmosis systems. Two different tests are routinely used to that end: the Silt Density Index (SDI) and the Modified Fouling Index (MFI0.45). SDI test, however, has disadvantages which make it unreliable. One disadvantage is that no linear relationship exists between SDI and the colloidal concentration in the water. Besides that, the SDI is not based on a filtration model. Finally, the SDI is not corrected for the testing condition parameters such as temperature, pressure and membrane properties.
The SDI test is simple and does not require advanced professional skills, but the above mentioned disadvantages make it unreliable. This work offers practical tools to resolve these disadvantages, such as a slide tool to calculate the SDI from the measured collection times. It also proposes a normalized SDI (SDI^+), and offers a line chart and slide wheel charts for this conversion, thus correcting for different test conditions and membrane resistance.
Finally, this paper introduces a new fouling index. This volume-based SDI, SDI_v, compares the initial flow rate with the flow rate after filtering the standard volume. It has a linear relationship to the particle concentration if complete blocking is the dominant fouling mechanism during the test, and is independent of testing conditions and membrane resistance. The mathematical model and experimental results show that SDI_v eliminates most of the disadvantages of the traditional SDI. The SDI_v is the second fouling index developed at the University of Twente, 30 years after the MFI0.45.

1. Introduction

Reverse osmosis (RO) membrane systems are used to desalinate seawater, among other things. However, flux decline due to fouling phenomena in the RO unit remains a challenge. Membrane fouling leads to increased resistance to transport across the membrane and the spacers, and hence to a decline in permeability. Significant fouling occurs even when several pretreatment steps are applied. Several types of fouling may take place in RO membrane systems, e.g. inorganic fouling or scaling, particulate and colloidal fouling, organic fouling, and biological fouling or biofouling. To minimize RO fouling and its impact, monitoring the fouling potential of the RO feed water is important. The American Society for Testing and Materials (ASTM) introduced the Silt Density Index (SDI) as a standard test for RO fouling potential due to particles. It compares the initial flow rate with the flow rate after 15 min of filtration using microfiltration (MF) membranes with an average pore size of 0.45 μm. MF membrane properties such as pore size, porosity, hydrophilicity, zeta potential and surface roughness affect the fouling rate during the SDI test [2–9], as do nature of the colloids and water properties [2,10–12]. Consequently, there are growing doubts about the predictive value of the SDI [12]. Several other deficiencies affect the accuracy and reproducibility of the SDI, such as [13]:

- Lack of a correction factor for temperature;
- Lack of correction for variations in membrane resistance;
- Lack of linear correlation with the concentration of colloidal/suspended particles.

Nevertheless, the SDI test has been applied for decades [1] and is used worldwide for various purposes such as comparing different pretreatment methods [14,15], design of new desalination plants [16,17] and performance monitoring [18].

2. Theory and background

This section describes the two fouling indexes SDI and MFI0.45. It also briefly summarizes the mathematical relation between SDI and MFI which was developed in previous work. Finally, four mathematical models describing the influence of different fouling mechanisms on the SDI are presented.

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2.1. Definition of SDI

To determine the SDI, the rate of plugging of a membrane filter with pores of 0.45 μm and a diameter of 47 mm is measured at 207 kPa, in the following three steps:

1) The time t_1 it takes to filter the first 500 mL is determined.
2) Usually after 15 min (t_f), the time t_2 required to filter another 500 mL is determined.
3) The index is then calculated with the following formula.

$$SDI = \frac{100\%}{t_f}\left(1-\frac{t_1}{t_2}\right) = \frac{\%P}{t_f}. \tag{1}$$

If the plugging ratio (%P) exceeds 75%, a shorter period t_f must be taken, e.g. 10, 5 or 2 min.

2.2. Modified Fouling Index

The Modified Fouling Index (MFI0.45) was derived by Schippers and Verdouw in 1980 [13]. To determine the MFI0.45, the flow through the membrane filter is measured as a function of time.

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

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

The MFI0.45 (in s/m^6) is derived from the slope in the relation t/V vs. V, $tg\alpha$, at a temperature of 20 °C, a pressure of 207 kPa, and a membrane surface area of $13.8 \times 10^{-4}\ m^2$ (47 mm diameter). It is corrected for temperature and pressure and is therefore independent of temperature and pressure.

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

$$\mu = 0.497 \times (T + 42.5)^{-1.5} \tag{3}$$

2.3. Relationship between SDI and MFI

We developed a mathematical model describing the relationship between SDI and MFI. It can be used to calculate SDI as a function of MFI and the testing condition parameters [19]:

$$SDI = \frac{100}{t_f(\ min)}\left(1-\frac{\mu \cdot R_M + MFI \cdot V_c \cdot \Delta P \cdot A_M}{MFI \cdot V_c \cdot dP \cdot A_M + \sqrt{\mu^2 \cdot R_M^2 + 4 \cdot MFI \cdot dP^2 \cdot A_M^2 \cdot t_f}}\right) \tag{4}$$

MFI	measured MFI (s/m^6)
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, usually 15 min (900 s)
ΔP	applied pressure (Pa)
μ	water viscosity (Pa.s)

2.4. Fouling model

Hermia [20] described four empirical models that correspond to four basic types of fouling: cake filtration, intermediate blocking, standard blocking, and complete blocking. The parameters considered by these models have a physical meaning and contribute to the comprehension of the mechanisms of membrane fouling. These models were developed for dead-end filtration and are based on constant-pressure filtration laws. They are summarized in Table 1, where:

w_R	represents the specific cake resistance and is defined as the volume of feed water per unit area for which the cake resistance is equal to the membrane resistance;
w_A	represents the pore blocking potential and is defined as the volume of feed water per unit area that contains enough particles to block the pores completely; and
w_V	represents the pore filling potential and is defined as the amount of feed water per unit area that contains enough particles to fill the pores completely.

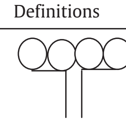
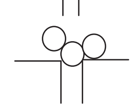
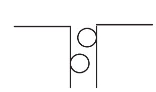
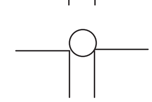
We developed a mathematical model to determine the filtrated volume V as a function of the filtration time t [22]:

$$V((t)) = \begin{cases} \frac{A_M \cdot R_M^{1-m}}{C \cdot (1-m)}\left(\left(1 + \frac{\left(2-m \cdot C \cdot \Delta P \cdot R_m^{m-2} t\right)}{\mu}\right)^{\frac{1-m}{2-m}} - 1\right), & m \neq 1, 2 \\ A_M \cdot w_A \ln\left(1 + \frac{\Delta P \cdot t}{w_A \cdot \mu \cdot R_M}\right), & m = 1 \\ A_M w_A \left(1 - e^{-\frac{\Delta P \cdot t}{w_A \cdot \mu \cdot R_M}}\right), & m = 2 \end{cases} \tag{5}$$

The time t to collect filtration volume V can be calculated by inverting Eq. (5):

$$t(V) = \begin{cases} \frac{\mu}{(2-m) \cdot C \cdot \Delta P \cdot R_M^{m-2}}\left(\left(\frac{V \cdot C \cdot (1-m)}{R_M^{1-m} \cdot A_M} + 1\right)^{\frac{2-m}{1-m}} - 1\right), & m \neq 1, 2 \\ \left(e^{\frac{V}{w_R \cdot A_M}} - 1\right) \cdot \frac{R_M \cdot w_R \cdot \mu}{\Delta P}, & m = 1 \\ \ln\left(\frac{A_M \cdot w_A}{A_M \cdot w_A - v}\right) \cdot \frac{R_M \cdot w_A \cdot \mu}{\Delta P}, & m = 2 \end{cases} \tag{6}$$

Table 1
Definition of the four fouling mechanisms. The parameters m and C relate to the fouling mechanisms and particle concentration. Total resistance is a function of filtration state w [21].

Details	Definitions	m	C
Cake filtration		0	$\frac{R_M}{w_R}$
Intermediate blocking		1	$\frac{1}{w_A}$
Standard blocking		1.5	$\frac{2}{w_V R_M^{1.5}}$
Complete blocking		2	$\frac{1}{w_A R_M}$