New parameter for monitoring fouling during ultrafiltration of WWTP effluent

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Abstract Variations in water quality of waste water treatment plant (WWTP) effluent complicate ultrafiltration of this feed water. Traditional parameters do not provide sufficient information to explain the fouling of membranes during ultrafiltration of WWTP effluent. New parameters for measuring and monitoring the fouling potential of feed water for ultrafiltration membranes need to be developed. The normalised membrane fouling index for ultrafiltration membranes (MFI-UF$_n$) can be used as such and is according to the cake filtration theory calculated from the ratio of filtration time and filtration volume as a function of the filtration volume.

MFI-UF$_n$ can be calculated from both experiments with constant Trans Membrane Pressure (TMP) and from experiments with constant flux. This parameter can also be calculated independent of the scale of the experiment.

Results show that differences in fouling potential can be measured for various feed waters using the same membrane type and for various membrane types using the same feed water. Variation in feed water quality leads to a deviation of the MFI-UF$_n$, as was found especially for WWTP effluent. The applied TMP influences the value of the MFI-UF$_n$, indicating cake compression when applying a higher TMP. MFI-UF$_n$ can be used to identify the effect of pre-treatment methods, which is useful when using WWTP effluent as feed water for an ultrafiltration processes.

Keywords Fouling; parameter; prediction; pre-treatment; ultrafiltration; waste water treatment plant effluent

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Introduction

General

Membrane filtration is a new technology that is rapidly expanding in the area of drinking water preparation. During the last decade the treatment of WWTP effluent especially by ultrafiltration (UF) is getting growing attention. However, for this type of water the fouling tendencies seem to be rather complicated. This may be due to the great variations in quality of the effluent, during night and day, winter and summer and dry and rainy weather. Also the conventional parameters like COD, BOD, Suspended Solids, turbidity and nutrients give insufficient information on the expected or occurring membrane fouling. Therefore, if a parameter or a set of parameters can be developed giving an indication of the membrane fouling properties, the whole membrane filtration process can be optimised. With this parameter the fouling properties of the feed water can be monitored, the process conditions can be adjusted and the long-term fouling properties of the feed water can be predicted. The final result will be a more stable process with constant fluxes together due to better cleaning strategies and other process conditions. Hereby increasing the membrane lifetime and decreasing the cost per cubic metre of produced water.

Filtration mechanisms

Fouling is defined by IUPAC (Koros *et al*., 1996) as: “the process resulting in loss of performance of a membrane due to deposition of suspended or dissolved substances on its external surfaces, at its pore openings, or within its pores”. Fouling can be subdivided in essentially five mechanisms, each monitored as a build up of resistance (R_x):

- adsorption inside the membrane pores (R_a);
- blocking of the membrane pores (R_p);
- concentration of foulants near the membrane surface, also called concentration polarisation (R_{cp});
- deposition on the membrane surface forming a cake layer (R_c);
- compression of the cake layer (R_{cc}).

During filtration these mechanisms may occur simultaneously. The average pore diameter and the porosity of the membrane mainly determine the initial resistance of the membrane (R_m). According to data obtained from this research, in ultrafiltration of WWTP effluent these mechanisms can increase the initial value of the membrane resistance up to three times or more.

Monitoring filtration characteristics

For the prediction of the fouling potential of Reverse Osmosis (RO) membranes several fouling indices have been developed. The most widely used are the Silt Density Index (SDI) and the Modified Fouling Index (MFI). These fouling indices are determined with simple membrane tests using a 0.45 μm Millipore filter. If feed water for RO exceeds a certain SDI or MFI value, the RO membrane is expected to foul more rapidly and a lower flux is required (Taylor and Jacobs, 1997). To incorporate also the smaller particles in the MFI, Boerlage *et al.* (1998) examined the use of ultrafiltration membranes for measuring the Modified Fouling Index using ultrafiltration membranes (MFI-UF).

Methods

Measuring fouling of ultrafiltration membranes

During dead-end operation of ultrafiltration, the filtration volume versus filtration time is continuously measured. These filtration curves are characteristic to the combination of the used feed water and the used membrane. The hydraulic characteristics of the membrane

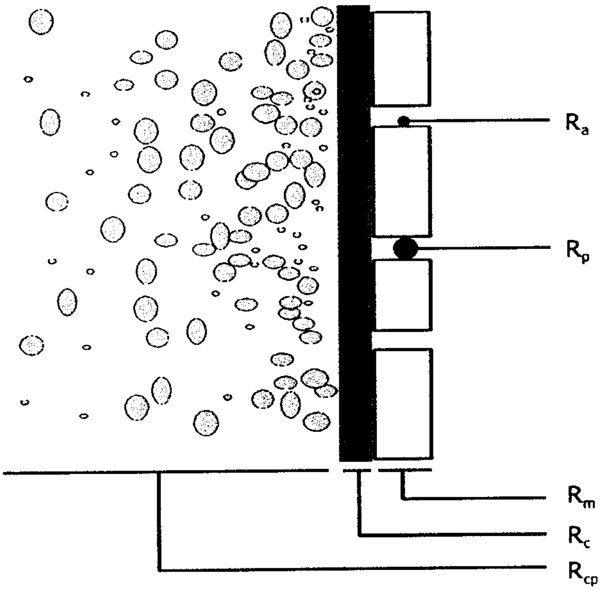

Figure 1 Resistance of a fouled membrane contributed to various fouling mechanisms: R_a = adsorption, R_p = pore blocking, R_m = initial membrane resistance, R_c = cake filtration, R_{cp} = concentration polarisation (van den Berg, 1988)

module and the process conditions are of minor interest for the development of the resistance. As a result the same filtration curve as measured in pilot-scale can be measured in a lab-scale unit. When using the same feed water and the same membrane type the produced volume versus time should give the same relation, independent of the scale.

According to the cake filtration model the following relationship between filtration time and volume can be derived, assuming constant TMP (Boerlage *et al.*, 1998):

$$\frac{t}{V}=\frac{\eta\cdot R_m}{\Delta P\cdot A_m}+\frac{\eta\cdot I\cdot V}{2\cdot\Delta P\cdot A_m{}^2} \tag{1}$$

in which: t = filtration time (s)

V = total produced permeate volume (m^3)

η = dynamic viscosity ($N.s/m^2$)

R_m = membrane resistance (m^{-1})

ΔP = Trans Membrane Pressure (N/m^2)

A_m = membrane area (m^2)

I = fouling index, product of specific cake resistance and particles concentration ($1/m^2$)

This equation predicts a linear relationship between *t/V* and *V* during cake filtration. In figure 2 the theoretically measured filtration curve is shown. In this figure three different regions are determined, which correspond to (1) pore blocking, (2) cake filtration and (3) cake filtration with compression. The slope of the curve in the second region relates to the cake filtration process and may be used as an index for the fouling potential of feed water according to Equation (1).

From the slope the MFI-UF at A = 1 m^2 and TMP = 1 bar (MFI-UF_n) is calculated according to Equation (2):

$$MFI-UF_n=\frac{\eta_{20}}{\eta_T}\cdot A_m{}^2\cdot\frac{d(t/V)}{dV} \tag{2}$$

in which: MFI-UF_n = MFI-UF normalised to A = 1 m^2 and TMP = 1 bar (s/l^2)

η_{20}, η_T = viscosity of feed water at T = 20°C and T °C respectively ($N.s/m^2$)

The relation between viscosity at 20°C and T °C is shown in equation (3), with T being the Temperature (°C) (Huisman, 1996):

$$\frac{\eta_{20}}{\eta_T}=\frac{(T+42.5)^{1.5}}{(20+42.5)^{1.5}} \tag{3}$$

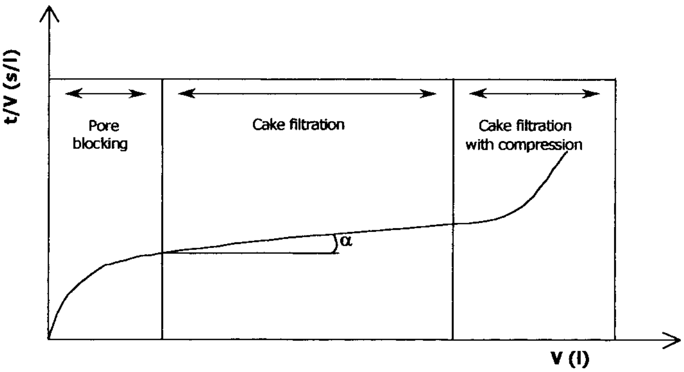

Figure 2 Ratio of filtration time and filtration volume as a function of the total volume of filtrated feed water (at constant TMP) indicating three filtration mechanisms: blocking filtration, cake filtration and cake filtration with compression; tan α is used as the fouling index

Experiments

Filtration curves are measured using tubular membranes. The experiments were performed both on lab-scale (membrane area: 2–8×10^{-3} m^2) and on pilot-scale (membrane area: 15–70 m^2). Based on experiments on pilot-scale, similar membrane types were used in lab-scale experiments. An overview of the membrane types used in the various experiments is shown in Table 1.

Lab-scale experiments

Filtration curves were measured on lab-scale using various membranes on basis of feed water with varying quality, i.e. WWTP-effluent, WWTP-effluent + coagulant (Poly Aluminium Chloride (PAC), 0.5 mg Al^{3+}/l) and filtrate of a deep-bed filter (Table 2). To take into account the varying feed water quality, each combination of feed water and membrane type was 4 to 8 times tested and performed on several days.

A schematic drawing of the apparatus used for measuring filtration curves is shown in Figure 3. The membranes are fitted into gas-connection tubes (FESTO) and watertight glued. For each experiment a new membrane is used, which has been soaking in a chlorine solution (200–300 ppm).

Before the experiment starts the clean water flux of the membrane is measured. To provide a constant feed composition in the whole system, two times the volume of the buffer

Table 1 Characteristics of the membranes used in the experiments

Membrane type	Location	Average pore size^c (nm)	Internal Diameter (mm)	Lab/Pilot
1 – PVDF^a	WWWTP Ede	30	14.4	Lab
2 – PVDF	WWTP Ede	30	5.2	Pilot
3 – PES/PVP^b	WWWTP Ede/WWTP Kaffeberg	20	1.5	Lab/Pilot
4 – PES/PVP	WWTP Ede	10–30	0.8	Pilot

^{a} hydrophilic Poly Vinyl Idene Fluoride; ^{b} hydrophilic Poly Ether Sulfone/Poly Vinyl Pyrrolidone; ^{c} as indicated by manufacturer

Table 2 Quality of feed water used in lab-scale and pilot-scale experiments

		WWTP Ede			WWTP Kaffeberg		
		Effluent	Effluent+^{a}	Filtrate	Effluent	Effluent+	Filtrate
COD	mg COD/l	22	36	16	36	–	32
Turbidity	FTE	1.8	2.5	0.5	4	–	<1
Suspended Solids	mg SS/l	5.3	3.0	1.3	>4	–	<2
P_{tot}	mg P/l	0.15	0.15	0.15	2.8	–	2.4

^{a} Effluent + PAC (0.5 mg/l)

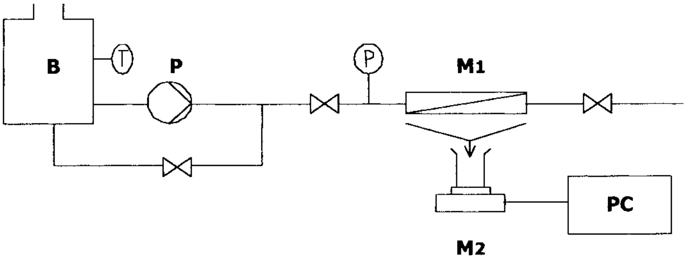

Figure 3 Lab-scale unit used for measuring filtration curves and calculating MFI-UF$_n$.
B: Buffer tank, T: Temperature, **P**: Pump, P: Pressure, **M**1: Membrane, **M2**: Mass Balance, **PC**: Computer

tank ($V = 25$ l) filled with feed water is flushed through the system. After starting the experiment the feed water temperature is measured. The TMP is manually kept constant at 1 bar. The ultrafiltration permeate is collected on a mass balance (Mettler Toledo, 0–2000 g) connected to a computer with data-analyses software. The experiment is stopped when the amount of produced water rapidly decreases. After each experiment the whole system is flushed through with chlorinated drinking water (200–300 ppm) in order to prevent bacterial growth. The collected data are processed in a spreadsheet programme from which the MFI-UF$_n$ can be calculated.

Pilot-scale experiments

The pilot-scale installation is equipped with a membrane area of 15 up to 70 m^2. The feed water for the pilot is taken from the outlet of the WWTP and from the outlet of a deep bed filter. Filtration curves are measured for WWTP-effluent, WWTP-effluent + PAC and filtrate on several days applying various constant fluxes (20, 40, 70 and 100 l/m^2.h). Due to the constant fluxes during the experiments the TMP gradually increases, starting at 0.2–0.4 bar and stopped at 0.8 bar.

In order to relate the measured data of the constant flux experiments (pilot-scale) to the data of the constant TMP experiments (lab-scale), the constant flux data have to be transformed. It is assumed that compression of the cake does not occur during the experiment, as is found to be reasonable within a short time interval. The normalised flux (J_n in l/m^2.h.bar at 20°C) is calculated by dividing the constant flux by the increasing TMP. As shown in figure 4-I, J_n decreases within time. The transformed time (t^*) is calculated for each combination of J_n and the produced volume (V), resulting in figure 4-II. With t^* and V the relationship between t^*/V and V is plotted and the MFI-UF$_n$ is calculated from the slope of the linear area of the curve.

Results and discussion

Some typical curves obtained from the lab-scale experiments are shown in Figure 5. The slope of the curve measured for permeate indicates a low MFI-UF$_n$ and therefore a low fouling potential for the applied ultrafiltration membrane. The slope of the curve measured for deep-bed filtrate indicates a much higher fouling potential for filtrate than for permeate.

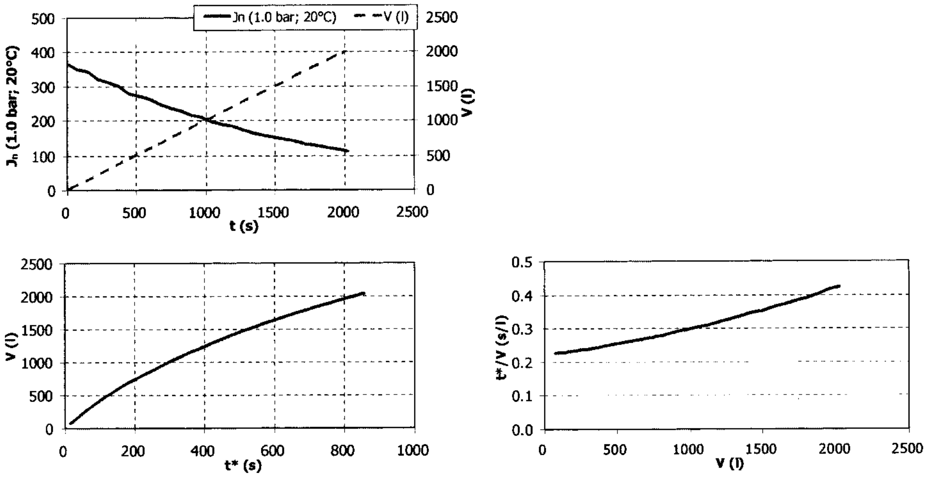

Figure 4 Transformation of constant flux data into constant TMP data.

Curve I – V versus t at constant flux; J_n is constant flux divided by increasing TMP; Curve II – V versus transformed time (t^*), calculated from J_n and V; Curve III – t^*/V versus V, the slope giving the MFI-UF$_n$

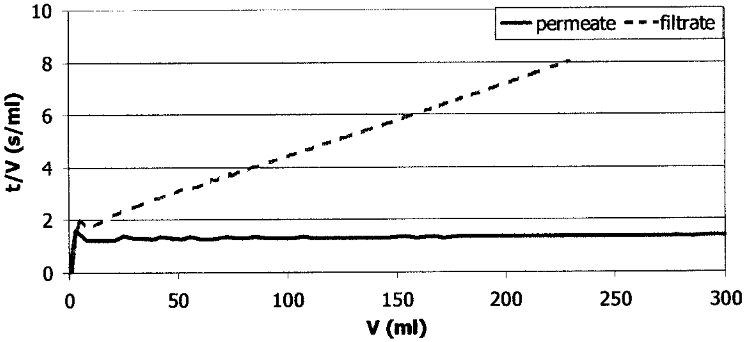

Figure 5 Filtration curve *t/V* versus *V* measured at constant TMP (1.0 bar), using membrane type 3 (A_m= 0.0021m^2); MFI-UF$_n$ of ultrafiltration permeate is 0.002 s/l^2; MFI-UF$_n$ of deep-bed filtrate is 0.11 s/l^2

The same curves have been calculated from the constant flux experiments (pilot-scale). A typical curve is plotted in Figure 6 in which the effluent+PAC has a MFI-UF$_n$ of 0.03 s/l^2, using membrane type 2.

In Table 3 the results of the various experiments are presented. Using the same membrane type but different feed water, the MFI-UF$_n$ has a different value, found both in lab- and pilot-scale experiments. This indicates a characteristic fouling potential for each feed water with the used UF-membrane. The MFI-UF$_n$ for filtrate is lower than for WWTP-effluent, indicating a lower fouling tendency for the used membrane. This corresponds to other research results (van Hoof *et al.*, 1998). Therefore the MFI-UF$_n$ may be used for an estimation of the influence of pre-treatment methods.

The standard deviation of the MFI-UF$_n$ is different for each feed water. A lower deviation relates to a more constant feed water quality. The MFI-UF$_n$ of filtrate has for each set of experiments a lower standard deviation than the effluent. Various researchers found that for filtrate the water composition is rather constant. The water quality had been evaluated using various traditional parameters. It is also known from literature that the water quality of WWTP-effluent heavily fluctuates within time (Chang *et al.*, 1996; van Hoof *et al.*, 1998; de Koning and van Nieuwenhuijzen, 1999).

The experiments performed at WWTP Ede, using different membrane types show that membrane type 2 has a two times higher MFI-UF$_n$ than membrane type 4. The membrane type clearly effects the absolute value of the MFI-UF$_n$. Many researchers describe that fouling is influenced by the composition of the membrane (Doyen *et al.*, 1998; Galjaard *et al.* 1998).

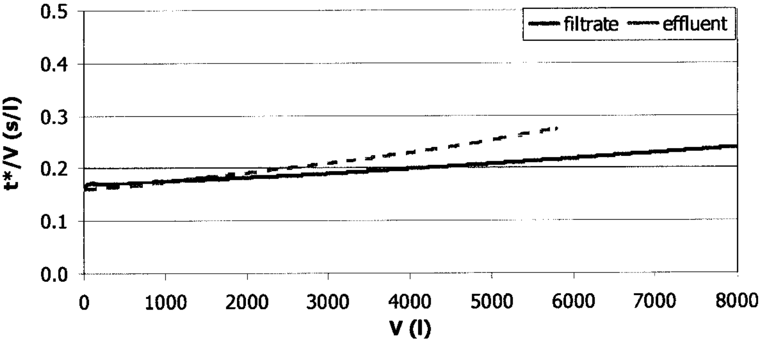

Figure 6 Filtration curve t^*/V versus *V* measured at constant flux (100 l/m^2.h), using membrane type 2 (A_m = 70 m^2); MFI-UF$_n$ of deep-bed filtrate is 0.03 s/l^2; MFI-UF$_n$ of effluent is 0.08 s/l^2

Table 3 MFI-UF$_n$ (s/l^2) measured in lab- and pilot-scale experiments at the WWTP Ede and WWTP Kaffeberg, using four membrane types and various feed waters

Feed	WWTP Ede		WWTP Kaffeberg	
	Lab[a]	Pilot[b]	Lab[d]	Pilot[d]
Effluent	0.08 ± 0.025 0.	06 ± 0.020 0.13 ± 0.030[c]	0.15 ± 0.025 0.	13 ± 0.025
Effluent + PAC	–	0.07 ± 0.040	–	0.09[e]
Filtrate	0.06 ± 0.020	0.04 ± 0.005	0.14 ± 0.045	–

[a] membrane type 1; [b] type 4; [c] type 2; [d] type 3; [e] based on one experiment

The experiments on WWTP-effluent performed on WWTP Kaffeberg show a higher MFI-UF$_n$ for the lab-scale experiments in comparison to the pilot-scale experiments. These higher values may theoretically be related to compressibility of the cake layer. For transforming the data measured at constant flux experiments (pilot-scale) the assumption has been made that compression does not occur. According to van den Berg (1988) and Boerlage *et al.* (1998) compression of the cake results in higher resistances. Therefore the measured fouling potential has to be higher when applying a higher TMP. In the lab-scale experiments the applied TMP is set to 1 bar, in the pilot-scale experiments the average applied TMP is 0.5 bar (± 0.2 bar, depending on the applied flux). The higher TMP corresponds to a higher MFI-UF$_n$ for the lab-scale experiments.

Finally it must be stated that the MFI-UF$_n$ only measures the fouling potential of a feed water and not the reversibility of the occurring fouling. Nevertheless a high instantaneous fouling potential frequently also refers to high long term fouling characteristics (Doyen *et al.*, 1998; Galjaard *et al.*, 1998).

Conclusions

The MFI-UF$_n$ is a new parameter for measuring the fouling potential of ultrafiltration feed water. MFI-UF$_n$ can be calculated from the ratio of filtration time and filtrate volume (t/V) as a function of the total filtrate volume.

Constant flux data can be transformed to constant TMP data, in both cases showing similar fouling mechanisms. Differences may be related to cake compression.

The membrane type influences the value of the MFI-UF$_n$, indicating that the fouling tendency of the membrane is related to the membrane type.

Differences in MFI-UF$_n$ using the same membrane type with different feed waters indicate a difference in filterability of this feed water. According to the MFI-UF$_n$ values found in this research, deep bed filtration may improve the (UF-) filterability of the WWTP-effluent.

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