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Combined effect of periodic backwashing and forward flushing on fouling mitigation in a pressurized UF membrane process for high turbid surface water treatment

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ABSTRACT

The present study highlights the effect of the periodical cleaning by backwashing and forward flushing, on fouling mitigation in a pressurized ultrafiltration (UF) membrane process treating high turbid surface water. The results showed that coupling backwashing and forward flushing has a better effect on membrane permeability recovery than applying only one cleaning technique. Moreover, during periodical cleaning, starting by backwashing followed by forward flushing would allow a better membrane recovery. A cake formation model was used to simulate the global trend of the relative membrane permeability. The modelling study enabled to quantify the effect of different cleaning strategy on fouling mitigation.

Keywords: Surface water treatment; High turbid water; Membrane ultrafiltration; Physical cleaning; Forward flushing; Back washing

1. Introduction

Water scarcity is a huge concern facing humanity nowadays because freshwater represents just 2.5% of earth's water and is increasingly threatened by urbanization, industrialization and climate change [1]. Surface water contamination is revealed by high turbidity due to the accumulation of suspended matter including silt, clay, finely divided organic and inorganic matter, dissolved organic compounds and microorganisms [2]. Many factors could be behind surface turbidity water increase such as the high flow rate in water body, soil erosion, urban runoff, wastewater and septic system effluent and algal bloom. To reduce its turbidity, many works have been conducted to treat the surface water using conventional methods such as coagulation–flocculation, sedimentation and adsorption [3,4]. Nowadays, more interest has been taking in membrane filtration technology and especially ultrafiltration (UF) and microfiltration, producing excellent effluent (permeate) qualities, low footprint required and easy to operate [5,6]. Nevertheless, membrane fouling is still main issue behind membrane productivity decrease [7]. The fouling demands much energy consumption and shortens membrane life-time [8,9]. Membrane fouling is caused by deposit of foulant material on membrane surface and/or membrane pore matrix leading to decrease in its permeability. The main foulants identified when treating surface water were the particulate/colloidal materials, proteins like substances as well as humic and fulvic acids [10–14].

To control membrane fouling, physical cleaning by membrane relaxation, backwashing and forward flushing is often

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applied periodically [15–17]. For the in-situ cleaning with membrane permeate, time duration and frequency are still arbitrary. Additionally, most of the bench-scale designs have not included a backwashing and/or forward cleaning cycle since it is not aimed at investigating the effectiveness of backwashing in removal of foulants [18]. Periodic cleaning can sometimes halt filtration performance because produced permeate itself can affect the system productivity negatively. As a result, an optimization of backwashing cycle would be then necessary to maximize membrane productivity while increasing the membrane lifespan [19].

This work investigates combined effect of backwashing and forward flushing on membrane fouling in pressurized membrane process (PMP) in treating highly turbid surface water. Although most of previous works focused on the effect of dissolved organic matter on membrane fouling [20,21], this study highlighted the effect of the particulate colloidal matter consisting of silicate particles. By testing different cleaning strategies based on different operational frequencies, durations and order of cleanings by backwashing and forward flushing, this study can come up with an optimal protocol with PMP for high turbid surface water treatment.

2. Material and methods

2.1. Experimental setup

A laboratory scale pressurized UF membrane setup was developed as shown in Fig. 1. A hollow fibers polysulfone membrane module of 100 fibers, with a total area of 0.11 m^2, a mean pore size of 0.05 μm and an ID/OD of 0.9/1.4 mm was provided by Woojin construction Co., Ltd. and tested for this study. The membrane water permeability at 28°C ± 0.9°C was 594 ± 94 L m^{-2} h^{-1} bar^{-1}. Set-point permeate flux was maintained by microgear pump (WT3000-1JA, Longerpump, China). Flow rates and pressures were measured by impeller flow meter (FHK G1/4, Digmesa, Swiss) and digital pressure gauge (PSAN-L1CA, Autonics, Korea), respectively. System control and data registration were realized by PLC installed customized software. The system is operated continuously. The driving force of the filtration process is ensured by the feed pump, which enables feed solution to flow through the membrane matrix. A flow sensor downstream the membrane detects the permeate flux decrease due to membrane fouling and sends a signal to the feed pump controller to increase pump speed in order to maintain a constant permeate flux.

2.2. Membrane operation

A synthetic high turbid surface water with turbidity of 10 NTU was used. High turbidity was ensured by adding 50 mg L^{-1} of SiO_2 (Samchun Pure Chemical, Korea) with a mean particle size of 3 μm, to simulate the particulate colloidal matter. To prevent sedimentation of SiO_2 particle, the feed solution was stirred in the feed tank. To measure the turbidity of retentate and permeate solution, turbidity meter (2020we, LaMotte, USA) was used. Dead-end filtration experiments in outside-in mode were conducted at two constant permeate fluxes of 50 and 100 L m^{-2} hr^{-1} (LMH). To ensure the dead-end filtration mode, the discharge valve was closed during filtration process. Every 30 min of filtration, a periodical physical cleaning of 1 min by backwashing and/or forward flushing was applied using the permeate solution. The backwashing was performed by passing permeate from inside to outside of the fibers, which is reverse to filtration process. Forward flushing was performed by passing the permeate solution along the membrane surface to remove foulants deposited on the membrane. Forward flushing flux was equal to the considered permeate flux, while backwashing flux was two times higher than the permeate flux. The different cleaning frequencies and durations are detailed in Table 1. Filtration, backwashing and forward flushing processes are described in Fig. 2.

Membrane performance is evaluated in terms of normalized permeability expressed as follows:

$$\frac{L_p}{L_{p,0}} = \frac{J/\text{TMP}}{J/\text{TMP}_0} \tag{1}$$

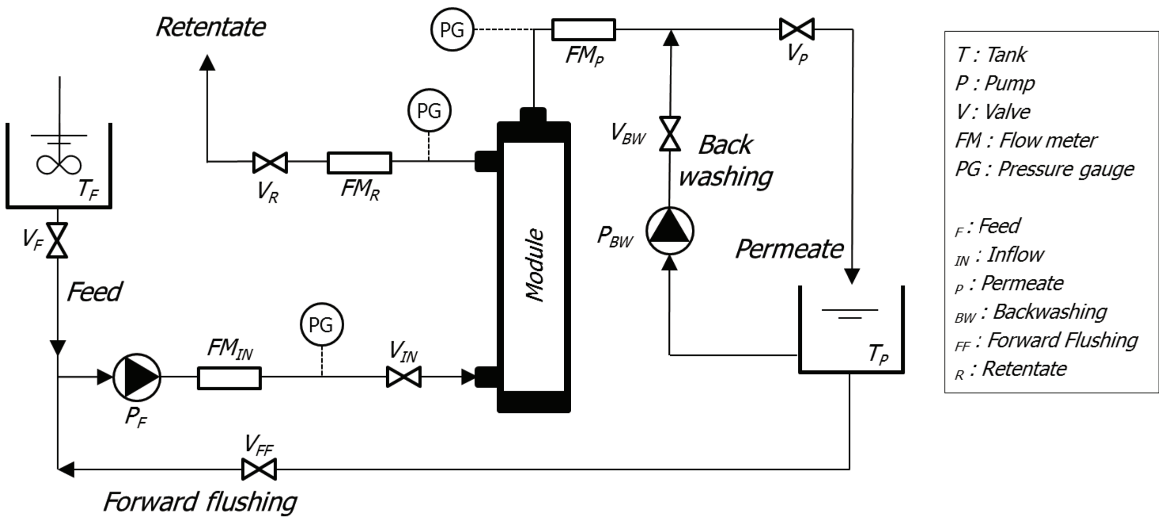

Fig. 1. Experimental setup of pressurized UF membrane system.

Table 1
Hydraulic cleaning condition in this study

Cleaning condition	Filtration	FF	BW	FF
FF	30 min	60 s		
BW	30 min		60 s	
FF/BW	30 min	30 s	30 s	
BW/FF	30 min		30 s	30 s

FF, forward flushing, BW, backwashing.

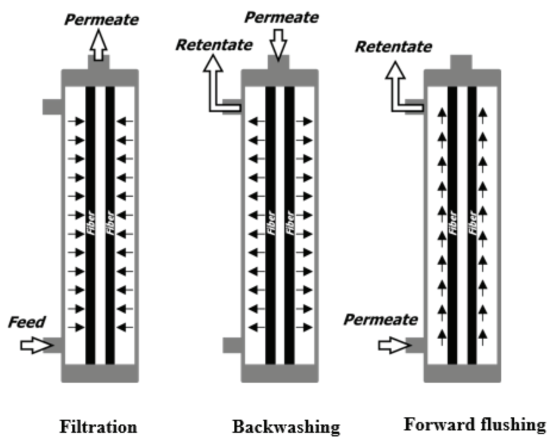

Fig. 2. Schematic description of the filtration, backwashing and forward flushing.

where L_p is the permeability (L m^{-2} h^{-1} bar^{-1}), $L_{p,0}$ is the initial permeability (L m^{-2} h^{-1} bar^{-1}), J is the permeate flux (L m^{-2} h^{-1}), TMP is the trans-membrane pressure (bar) and TMP_0 is the initial trans-membrane pressure (bar).

2.3. Modelling approach for fouling analysis

2.3.1. Model development

A modelling approach was used to better understand the fouling mechanisms behind permeability decrease in a PMP for surface water treatment when applying periodical cleaning by coupling backwashing and forward flushing.

The model aims at simulating the global trend of membrane normalized permeability variation with time at a constant permeate flux value, which will be proportional to the variation of the trans-membrane pressure (TMP) applied as shown in Eq. (1).

A simple model considering the cake formation as the only fouling mechanism was considered [22]. The model is based on a resistance in series model and Darcy's law to quantify the applied TMP:

$$\text{TMP} = J \cdot \mu \cdot \left(R_0 + R_c\right) \tag{2}$$

where J is the permeate flux (m^3 m^{-2} s^{-1}), μ is the permeate viscosity (Pa s), R_0 is the intrinsic membrane resistance (m^{-1}) and R_c is the cake resistance (m^{-1}).

The cake resistance expressed in Eq. (3) is assumed proportional to the deposit mass m and the specific cake resistance α (m kg^{-1}).

$$R_c = \frac{\alpha \cdot m}{A} \tag{3}$$

where A is the membrane area (m^2).

Based on mass balance realized on the membrane surface (Eq. (4)), the deposit mass variation is assumed as the difference between the matter deposited on the membrane surface by convective forces m_a (Eq. (5)) and the matter detached by the periodical cleaning applied m_{det} (Eq. (6)):

$$\frac{\mathrm{d}m}{\mathrm{d}t} = \frac{\mathrm{d}m_a}{\mathrm{d}t} - \frac{\mathrm{d}m_{\text{det}}}{\mathrm{d}t} \tag{4}$$

$$\frac{\mathrm{d}m_a}{\mathrm{d}t} = X \cdot J \cdot A \tag{5}$$

where X is the suspended matter concentration (kg m^{-3}), J is the permeate flux (m^3 m^{-2} s^{-1}) and A is the membrane area (m^2):

$$\frac{\mathrm{d}m_{\text{det}}}{\mathrm{d}t} = \beta \cdot m \cdot \frac{\mathrm{d}m_a}{\mathrm{d}t} \tag{6}$$

where β is the fouling mitigation parameter expressed in kg^{-1}, which reflects the global effect of periodical cleaning on deposit mass mitigation.

2.3.2. Comparison of model and experimental data

To verify its validity, the proposed model was compared with the experimental data of normalized permeability registered on the pressurized membrane system. The least squares method on MATLAB software was used for fitting the model with experimental data as well as to identify the model parameters which are not determined experimentally. This method is based on optimizing the model parameters permitting the minimization of the least squares (LS) function:

$$\text{LS} = \frac{1}{L_{p,0}} \Sigma \left(L_{p,\text{experimental}} - L_{p,\text{simulation}}\right)^2 \tag{7}$$

Table 2 shows the model parameters determined experimentally.

3. Results and discussions

3.1. Fouling behavior at 50 LMH permeate flux

The normalized membrane permeability was registered at a permeate flux of 50 LMH in absence of the periodical cleaning as well as for the different periodical cleaning strategies (Fig. 3). The results show that due to fouling phenomenon, the membrane lose only 10% of its permeability within 3 h without applying periodical cleaning which shows the efficiency of the pressurized membrane system to ensure high permeate flux while keeping a high permeability when treating high turbidity surface water. When applying periodical cleaning, a permeability recovery was observed which highlights the effect of periodical cleaning in fouling mitigation. Nevertheless, no significant difference was observed in

Table 2
Model parameters considered for model simulations

Parameters	Meaning	Values
J	Permeate flux (LMH)	100
A	Membrane area (m^2)	0.11
μ	Permeate viscosity (Pa s)	10^{-3}
X	Suspended matter concentration (g L^{-1})	50×10^{-3}
R_0	Intrinsic membrane resistance (m^{-1})	7.41×10^{11}

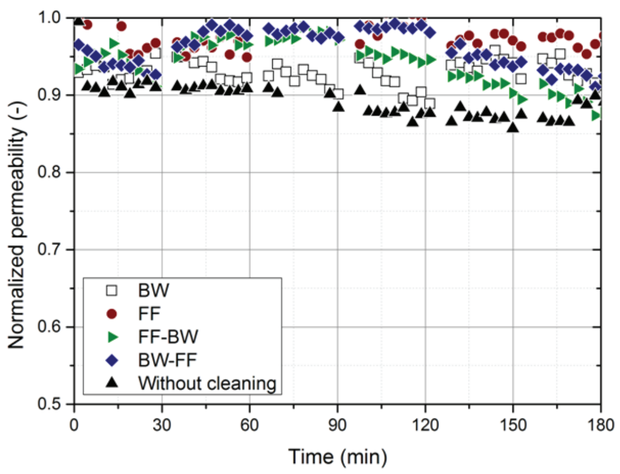

Fig. 3. Normalized membrane permeability registered with a permeate flux of 50 LMH for different cleaning strategy.

the effect of different cleaning strategies, which shows that when low fouling rate occurs, applying backwashing, forward flushing or coupling both techniques would have similar cleaning efficiency. Furthermore, the SiO_2 rejection by the membrane was higher than 99%, suggesting that the main fouling mechanism behind permeability loss was the formation of cake layer consisting of SiO_2 on membrane surface.

3.2. Fouling behavior at 100 LMH permeate flux

When increasing the permeate flux from 50 to 100 LMH, higher membrane fouling leads to a membrane permeability decrease of 40% when a continuous filtration is applied during 3 h (Fig. 4). A permeability recovery is observed when applying periodical cleaning, nonetheless, the recovery efficiency depends on the applied cleaning strategy. A permeability recovery of 26%, 39.2%, 42.3% and 52.5% was obtained when applying BW, FF, FF followed by BW and BW followed by FF, respectively. Higher membrane recovery efficiency was observed when coupling both backwashing and forward flushing compared with the application of only one of them. This result is proven also by Kennedy et al. [23], claiming that backwashing would be effective to unblock the membrane pores while forward flushing would be effective to eliminate the cake layer. Moreover, the lowest permeability recovery was obtained when applying only periodical backwashing and this could be explained by the fact that in the pressurized

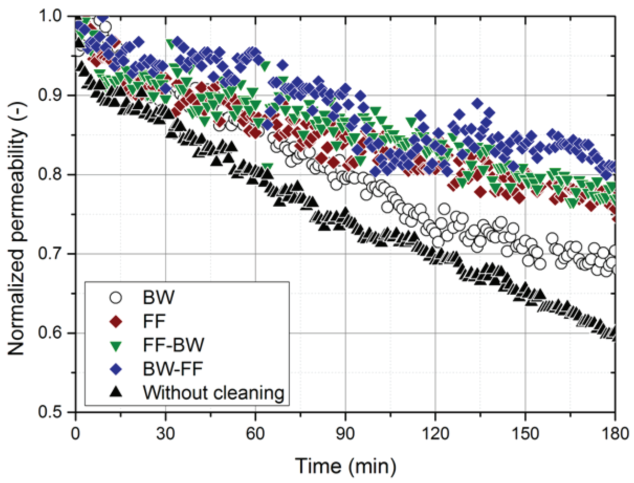

Fig. 4. Normalized membrane permeability obtained at a permeate flux of 100 LMH for different cleaning strategies.

membrane system, the material detached by backwashing effect could be trapped within the module case and deposited again during the following filtration phase. This phenomenon highlights the advantage of applying forward flushing phase after backwashing to evacuate all detached matter, which explains the highest permeability recovery obtained when applying this strategy. Furthermore, similarly to the experiments realized at 50 LMH, SiO_2 rejection by the membrane was also 99% at a permeate flux of 100 LMH which shows turbidity removal should not be affected by permeate flux applied.

3.3. Quantifying cleaning effect by modelling approach

As detailed in section 2.2.2, the model was fitted with the membrane normalized permeability experimental data and the model parameters were identified using the LS method. Fig. 5 shows the fitting results between model and experimental data obtained with different cleaning strategies, without periodical cleaning (Fig. 5(a)), with a periodical BW of 60 s every 30 min of filtration (Fig. 5(b)), a periodical FF of 60 s every 30 min of filtration (Fig. 5(c)), a periodical FF of 30 s followed by 30 s of BW every 30 min of filtration (Fig. 5(d)) and a periodical cleaning of BW of 30 s followed by 30 s of FF every 30 min of filtration. Fig. 5(e) displays satisfactory fitting results, showing that the simple considered model was able to describe the global trend of normalized membrane permeability when different cleaning strategies are applied.

Two model parameters were identified by LS method which are the specific cake resistance α and the cleaning parameter β. The values obtained for each studied case are shown in Table 3.

Based on the identified values (Table 3), lower specific cake resistance values and higher cleaning parameter values are obtained when applying periodical cleaning which confirms its effect on fouling mitigation. Moreover, different values were obtained for different considered cleaning strategies, which highlights the effect of optimizing periodical cleaning. In fact lower α values and higher β values were obtained when coupling forward flushing and backwashing,

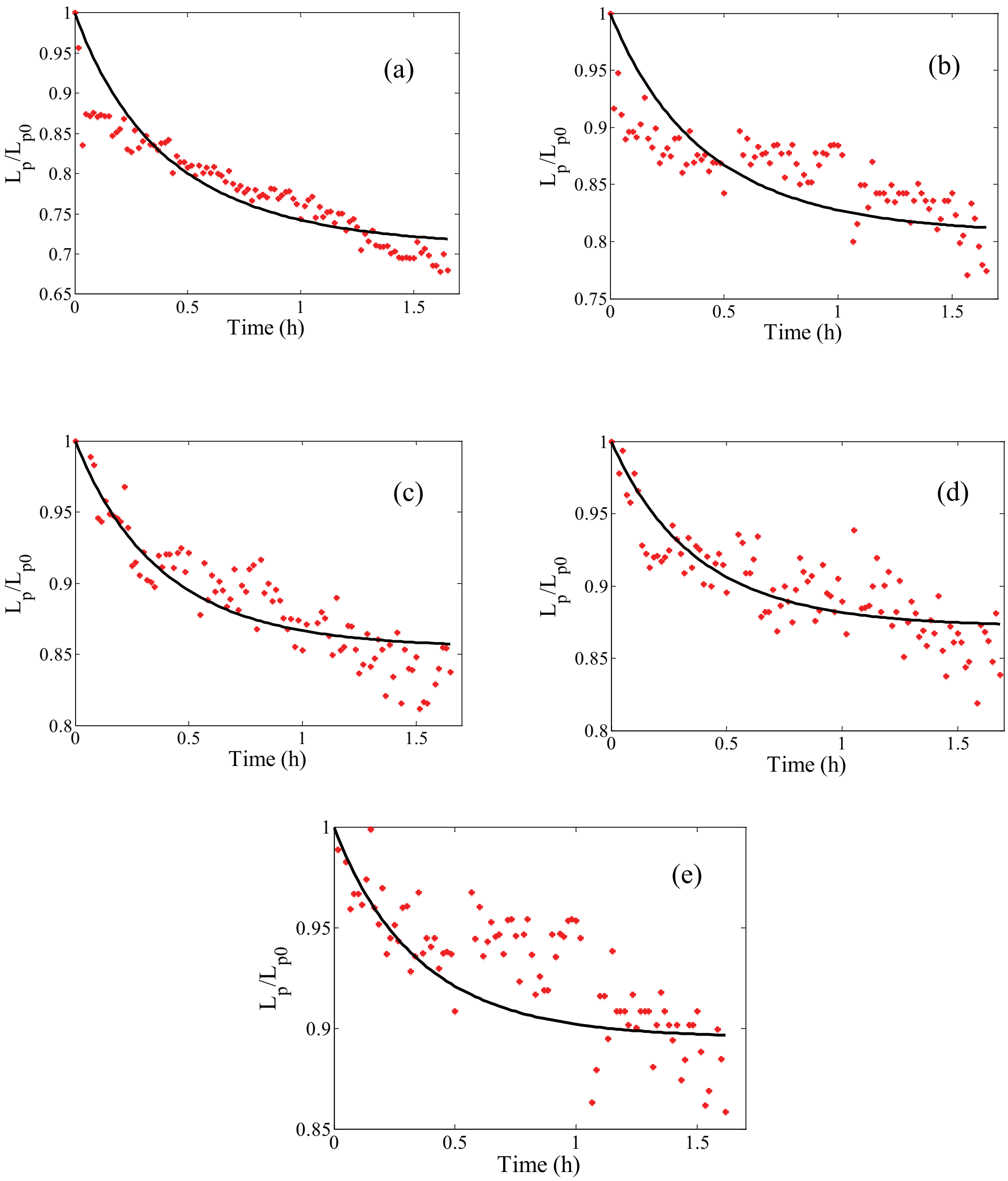

Fig. 5. Comparison of model simulations and normalized permeability experimental data for different cleaning strategies (a) without cleaning, (b) F/BW (30 min/60 s), (c) F/FF (30 min/60 s), (d) F/FF/BW (30 min/30 s/30 s), (e) F/BW/FF (30 min/30 s/30 s).

Table 3
Values of the identified model parameters

Cleaning strategy	α (m/kg)	β (kg^{-1})	LS
Without cleaning	$1.11 \times 10^{14} \pm 0.002$	367.3 ± 0.002	0.0925
F/BW (30 min/60 s)	$0.71 \times 10^{14} \pm 0.002$	400.2 ± 0.002	0.0720
F/FF (30 min/60 s)	$0.58 \times 10^{14} \pm 0.001$	460.5 ± 0.001	0.0262
F/FF/BW (30 min/30 s/30 s)	$0.52 \times 10^{14} \pm 0.001$	477.8 ± 0.001	0.0380
F/BW/FF (30 min/30 s/30 s)	$0.45 \times 10^{14} \pm 0.001$	520.3 ± 0.001	0.0350

F, filtration, FF, forward flushing, BW, backwashing.

than when only one cleaning process is used. Furthermore higher α value and lower β values were obtained when applying only periodical backwashing which could be explained by the fact that when applying backwashing in a pressurized membrane hollow fibers module, there is a risk that the detached matter are trapped within the module case and are again deposited on the membrane surface during the filtration phase. The application of forward flushing after backwashing would allow the evacuation of the detached matter from the membrane module. This phenomenon could explain the lowest values obtained for specific cake resistance and the highest value determined for the cleaning parameter obtained when applying periodical backwashing followed by forward flushing. The identified values of the model parameters meet the experimental results shown in the previous section.

4. Conclusions

This study highlighted the effect of the periodical cleaning by coupling backwashing and forward flushing on mitigating the fouling due to the deposit of particulate–colloidal matter on the membrane surface, in a pressurized UF membrane system treating high turbidity surface water. This study showed that coupling backwashing and forward flushing would be more efficient than applying only one cleaning technique. Moreover, a cake formation model was presented as a simple tool to better understand and quantify the effect of an optimized periodical cleaning on fouling control.

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Symbols

A — Membrane area, m^2
J — Permeate flux, $m^3\ m^{-2}\ s^{-1}$
L_p — Membrane permeability, $L\ m^{-2}\ h^{-1}\ Pa^{-1}$
$L_{p,0}$ — Membrane initial permeability, $L\ m^{-2}\ h^{-1}\ Pa^{-1}$
m — Deposit mass, kg
m_a — Mass of deposited matter by convection forces, kg
m_{det} — Mass of detached matter, kg
R_0 — Intrinsic membrane resistance, m^{-1}
R_c — Cake resistance, m^{-1}
TMP — Trans-membrane pressure, Pa
TMP_0 — Initial trans-membrane pressure, Pa
X — Suspended matter concentration, $kg\ m^{-3}$
α — Specific cake resistance, $m\ kg^{-1}$
β — Cleaning parameter, kg^{-1}
μ — Permeate viscosity, Pa s

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