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Influence of membrane surface regeneration frequency using back pulse method on the average permeate flux

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ABSTRACT

The paper presents results of modeling and optimization of microfiltration used to purification of river water in crisis conditions. The considered process was carried out in cycle. The cycle duration consisted of the time required to obtain desired volume of permeate with simultaneous accumulation of contaminants on the membrane surface and the time necessary for membrane regeneration. The latter part was connected with the loss of part of the produced permeate, consumed for membrane washing by means of the back pulse method. It was assumed that during the membrane regeneration, the membrane recovered its original state. All process cycles were identical. The analysis of the various forms of the performance index showed that in crisis conditions it was essential to ensure maximum performance of permeate production. Assuming the identical character of process cycles, the maximization of the cycle performance was crucial. A dependence of cycle performance on permeate production duration in one cycle was derived, also in reference to other factors treated as parameters. The study was equivalent to the study of the influence of the membrane regeneration frequency on the average permeate flux. Calculations were made for different values of the parameters. The data from the commercial Liqui-Flux®W02 module were used. The results showed that the optimal frequency of the membrane regeneration needed to be greater than the one commonly used in practice.

Keywords: Microfiltration; Regeneration frequency; Optimization

1. Introduction

The research presented in this paper concerns both modeling and optimization of membrane processes used to purification of water uptaken from a reservoir, resources of which, for modeling purposes, can be assumed as infinite. This definition of a reservoir can be conventionally attributed to, for example, a river.

Introducing the concept of an infinite reservoir resources should be understood as the assumption that the considered process can be carried out for any length of time. Obviously, it does not mean that the process is a steady-state one [1]. During the filtration, the membrane surface of becomes covered by deposit formed by contaminants present in the purified river water from the river, which are retained by the membrane. Therefore, it is necessary to performed a periodical regeneration of the membrane surface [2]. In the discussed study, the regeneration is obtained using the back pulse method. The emergence of membrane surface periodic regeneration makes the process cyclical. Moreover, if one accepts, that the membrane returns to its original state, the concerned process should be regarded as a cyclical operation, in which exactly the same cycles are run one after another. The duration of each cycle consists of the time required to obtain the desired amount of the permeate and the time necessary for the membrane regeneration, which is connected with the loss of part of the permeate consumed for membrane washing using the back pulse method.

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The considerations presented in this paper were applied to the membrane process carried out with the use of the installation shown in Fig. 1. River water was fed into the installation using a feed pump 1. At the exit of the pump, that is, at the inflow to membrane module 2, the water reached pressure p_1. The retentate leaving the membrane module was discharged into the river by a duct equipped with control valve 3. The permeate leaving the membrane module through the opened shut-off valve 4 was directed to the buffer permeate tank 5. Meanwhile, pump 6 was turned off, and shut-off valve 7 was closed. Part of the permeate collected in tank 5 was discharged as the desired product of the water purification process. The remaining part of the permeate was used to membrane surface regeneration using the back pulse method. The inclusion of the buffer permeate tank 5 within the installation made the permeate available for the membrane surface regeneration at any point of the process run. Regeneration of the membrane surface using the back pulse method took place after closing shut-off valve 4, opening shut-off valve 7 and turning pump 6 on. It was the operation of pump 6 that made the process of the membrane surface regeneration possible. The pump pressurized the permeate portion taken from tank 5 to pressure p_2, which was usually higher than pressure p_1, what enabled the run of the regeneration possible with no need of turning pump 1 off.

The aim of the considerations in this study was to evaluate the influence of the frequency of membrane surface regeneration using the back pulse method on the process performance index. Once this influence was determined, it would be possible to define the optimal frequency of the membrane surface regeneration, which would provide the extremum of performance index.

Virtually, all authors of manuals devoted to the process optimization stress the need to conduct a thorough analysis of the performance index formulated for the considered process. Obviously, such analysis must precede the optimization procedure itself [3,4]. It should be emphasized that if the optimization process applies to both, the installation design and the process performance at the installation, then the flux of net profit, which accompanies the implementation of the process, is the typical performance index. It is the difference between the flux of the resulting value and the flux of costs, both investment and operating ones. Such performance index should be maximized during the implementation of the optimization procedure. Yet, if the optimization refers to the process in an existing installation, the flux of operating costs accompanying the desired effect of the process will be the typical performance index. Such performance index should be minimized during the implementation of the optimization procedure. In specific cases, other forms of performance indices, which are usually simpler, may of course appear.

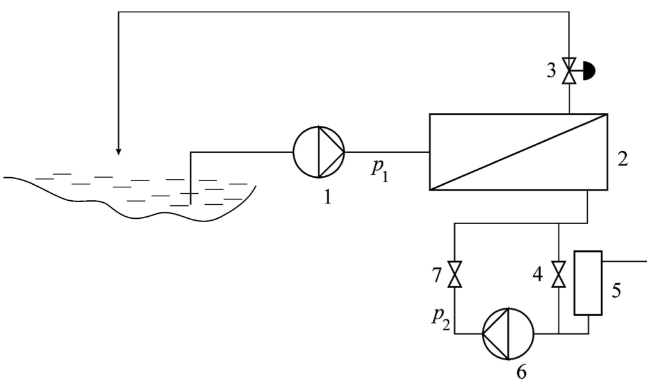

Fig. 1. The scheme of the considered membrane installation.

The process of river water purification, considered in this paper, is usually conducted in various crisis situations, which uses the same, already existing installation. Therefore, the way of implementing a specific process has no impact on the capital expenditure of the installation. Such a cost was incurred earlier. The implementation of the process, which can be, for example, a specific frequency of the membrane surface regeneration, may affect only operating costs. However, at crisis conditions, the achievement of the maximum productivity of the existing installation is crucial. Thus, in optimization considerations, the cost analysis may be totally skipped.

Hence, this paper is devoted to analysis of the influence of the frequency of the membrane surface regeneration using the back pulse method on the average permeate flux. The analysis results will enable determining the optimal frequency of the membrane surface regeneration required for maximum installation. Assuming that after each regeneration the membrane recovers its original state, it means that the considered process is a cyclical one, where exactly the same cycles are run one after another, and the problem of maximizing the overall installation performance corresponds to the problem of maximization the installation productivity revealed in single cycle of operation.

2. Mathematical model of the concerned process

During the membrane process, deposit settled down on the membrane surface increases the resistance of the whole partition. Resistance of clean (fresh) membrane R_m is constant, while resistance of deposit R_0 increases with the time. Instantaneous resistance of the membrane and sediment, R, may be described as given in Eq. (1):

$$R = R_m + R_0 \tag{1}$$

The amount of sediment accumulated on the membrane surface, and hence the resistance of the sediment, increase with the volume of produced permeate, V. Hence, the momentary resistance of the sediment R_0 may be expressed as the function of the volume of permeate V, relative to parameter ν, which describes the measure of the sediment resistance growth rate [Eq. (2)]:

$$R_0 = \nu V \tag{2}$$

Introducing the dependence (2) in Eq. (1) the one achieves Eq. (3):

$$R = R_m + \nu V \tag{3}$$

Instantaneous volumetric flow rate of permeate, Q_p, may be described with the known Ohm's equation [Eq. (4)] defined for the flow through porous partitions, where ΔP is transmembrane pressure:

$$Q_p = \frac{dV}{d\tau} = \frac{\Delta P}{R_m + \nu V} \tag{4}$$

Separation of the variables in Eq. (4) gives the differential Eq. (5):

$$(R_m + \nu V)dV = \Delta P d\tau \tag{5}$$

Eq. (5) may be integrated for time τ, within the range from $\tau = 0$ to $\tau = \tau_f$ where τ_f is the duration of microfiltration within a single cycle of the process, and volume V, within the range from $V = 0$ to $V = V_f$ where V_f is the volume of permeate obtained after τ_f.

$$\int_0^{V_f} (R_m + \nu V)dV = \Delta P \int_0^{\tau_f} d\tau \tag{6}$$

The integration of Eq. (6) gives Eq. (7):

$$\frac{1}{2}\nu V_f^2 + R_m V_f - \Delta P \tau_f = 0 \tag{7}$$

The solution of Eq. (7) in relation to V_f, which has a physical meaning, $V_f > 0$, is expressed by Eq. (8):

$$V_f = \frac{-R_m + \sqrt{R_m^2 + 2\nu \Delta P \tau_f}}{\nu} \tag{8}$$

The average permeate flow rate obtained in each cycle, $\overline{Q_p}$, may be defined as in Eq. (9). The numerator appearing on the right side of Eq. (9) describes the difference between volume V_f of the permeate produced during a single cycle, and the volume V_w of the permeate consumed in the same cycle to regenerate the membrane surface using the back pulse method. This difference describes the net permeate yield during a single process cycle. The yield is generated during a single cycle, which consists of the filtration time τ_f and the time necessary for washing the membrane surface τ_w. It is the total cycle duration, which appears in the denominator on the right side of Eq. (9).

$$\overline{Q_p} = \frac{V_f - V_w}{\tau_f + \tau_w} \tag{9}$$

The average permeate flow rate obtained in each cycle, $\overline{Q_p}$, constitutes the productivity of the process and describes the performance index of the process, which will be maximized.

The proportionality between the average volumetric flow of the permeate, $\overline{Q_p}$, for the cycle and the volumetric flow of the permeate used for washing the membrane, Q_w, with proportionality factor, ϑ, was assumed, and hence:

$$Q_w = \vartheta \overline{Q_p} = \vartheta \frac{V_f - V_w}{\tau_f + \tau_w} \tag{10}$$

The relationship between the permeate flux, which washes membrane, Q_w, the time of such the washing during in a single cycle, τ_w, and the volume of the permeate consumed for washing, V_w, results in a dependence (11)

$$Q_w \tau_w = V_w = \vartheta \frac{V_f - V_w}{\tau_f + \tau_w} \tau_w \tag{11}$$

After solving Eq. (11) in relation to V_w, and next introducing the dependence Eq. (8), it is achieved, that:

$$V_w = \frac{\vartheta V_f \tau_w}{\tau_f + (\vartheta + 1)\tau_w} = \frac{\vartheta \dfrac{-R_m + \sqrt{R_m^2 + 2\nu \Delta P \tau_f}}{\nu} \tau_w}{\tau_f + (\vartheta + 1)\tau_w} \tag{12}$$

Once Eqs. (8) and (12) are introduced to Eq. (9), the final form of the dependence of the average volumetric flow of the permeate produced during a single circle, $\overline{Q_p}$, on the duration of microfiltration single cycle, τ_f, is achieved. It should again be emphasized that the average flow rate of the permeate obtained during a single cycle, $\overline{Q_p}$, corresponds to the average volumetric flow of the permeate produced during the whole process of the river water purification.

$$\overline{Q_p}(\tau_f) = \frac{V_f - V_w}{\tau_f + \tau_w} = \frac{\dfrac{-R_m + \sqrt{R_m^2 + 2\nu \Delta P \tau_f}}{\nu} - \dfrac{\vartheta \dfrac{-R_m + \sqrt{R_m^2 + 2\nu \Delta P \tau_f}}{\nu} \tau_w}{\tau_f + (\vartheta + 1)\tau_w}}{\tau_f + \tau_w} \tag{13}$$

3. Estimation of applied parameters values

Factors such as R_m, ΔP, ν, τ_w and ϑ, which appear in Eq. (13), play the role of parameters. In order to estimate their values, data sheet for Liqui-Flux®W02 [5] membrane module with effective membrane surface area $F = 61$ m^2 was used (Table 1).

For the clean (fresh) membrane, Eq. (4) is simplified to the following form:

$$Q_p = \frac{\Delta P}{R_m} \tag{14}$$

Hence:

$$R_m = \frac{\Delta P}{Q_p} \tag{15}$$

Table 1
Selected properties of the membrane Liqui-Flux®W02 (based on [5])

Operating mode	Dead-end/ cross-flow
Typical flux range, filtration, $Lm^{-2}h^{-1}$	50–100
Typical flux range, backwash, $Lm^{-2}h^{-1}$	250
Filtrate flow rate range, m^3h^{-1}	3–9
Typical transmembrane pressure, filtration, kPa	10–70
Typical transmembrane pressure, backwash, kPa	50–200
Max. transmembrane pressure, filtration, kPa	250

In order to estimate the resistance of the clean membrane, we assumed that for such a membrane and at the highest possible transmembrane pressure, ΔP = 70 kPa, the highest filtrate flow rate was achieved, Q_p = 9 m^3h^{-1}, hence:

$$R_m = \frac{\Delta P}{Q_p} = 2.8 \cdot 10^7 \ \text{Pa} \cdot \text{s} \cdot \text{m}^{-3} \tag{16}$$

The results of calculations presented in the next chapter will be obtained for the value R_m specified by Eq. (16), and two other values, which are close to it, as well as for ΔP = 70 kPa.

Filtration practice indicates that for river water treatment for about 20 min = 1,200 s of operation, the total resistance of the membrane doubles in comparison with the initial value. Assuming that the initial resistance applies to a fresh membrane with resistance R_m, and the total resistance of the partition after 20 min of operation is R_{20}, the following equation may be formulated:

$$R_{20} = 2R_m \tag{17}$$

If the volume of permeate obtained during 20 min is marked as V_{20}, then on the basis of Eq. (3), the following relationship may be derived:

$$R_{20} = R_m + \nu V_{20} \tag{18}$$

The comparison of Eqs. (17) and (18) leads to the following relationship:

$$R_m = \nu V_{20} \tag{19}$$

The volume V_{20} may be expressed by means of Eq. (8) for microfiltration 20 min, τ_{20}, run. Hence, Eq. (8) is in the form:

$$V_{20} = \frac{-R_m + \sqrt{R_m^2 + 2\nu\Delta P\tau_{20}}}{\nu} \tag{20}$$

The comparison of Eqs. (19) and (20) leads to the following relationship:

$$\nu = \frac{3R_m^2}{2\Delta P\tau_{20}} = 1.4 \cdot 10^7 \ \text{Pa} \cdot \text{s} \cdot \text{m}^{-6} \tag{21}$$

Results of the calculations presented in the next chapter will be obtained for the value ν specified by Eq. (21), and two other values, which are close to it.

Practice shows that the time of washing the membrane, τ_w, ranges between several seconds and up to ca. a dozen of seconds. Results of the calculations will be obtained for three different values τ_w, which are within this very range.

Comparing the typical flux range for filtration and the typical flux range for backwash given in Table 1, it was decided to conduct all the calculations are presented in the next chapter for $\vartheta \approx 2$.

In some cases, the permeate flux is much more useful than the permeate flow. The permeate flux can be easily calculated as a quotient of the permeate flow and the membrane area. Finally, the Eq. (13) can be rewritten as:

$$\bar{J}_p\left(\tau_f\right) = \frac{1}{F}\frac{\dfrac{-R_m + \sqrt{R_m^2 + 2\nu\Delta P\tau_f}}{\nu} - \dfrac{\vartheta\dfrac{-R_m + \sqrt{R_m^2 + 2\nu\Delta P\tau_f}}{\nu}\tau_w}{\tau_f + \left(\vartheta + 1\right)\tau_w}}{\tau_f + \tau_w} \tag{22}$$

4. Results of the calculations

The results of calculations obtained with the use of Eq. (22) as well as the values of parameters estimated in the previous chapter and introduced to this equation, are presented in this chapter. It should be recalled that for the river water purification process in crisis conditions, the most important task is to achieve the maximum productivity of the existing installation. The considered process is cyclical. The duration of each cycle consists of the time required for the permeate production τ_f and the time necessary for the membrane surface regeneration τ_w. Assuming that during each regeneration of a membrane enables to recover its original state, hence, exactly the same cycles are run one after another. The problem of maximizing the installation productivity is, in this case, identical as the problem of maximization of the installation productivity for a single cycle operation. Eq. (22) describes the average permeate flux, $\bar{J}_p$, obtained during the cycle, as a function of microfiltration duration in a single cycle τ_f.

Figs. 2–4 show the character of function $\bar{J}_p = f(\tau_f)$ in a way that allows estimating the impact of different values of the considered parameters on the process solutions. The charts presented in Figs. 2–4 also enables the determination of the optimal microfiltration time periods during a single cycle. Thus, the discussed figures allow analyzing the influence of the membrane surface regeneration frequency, with the use of the back pulse method, on the average permeate flux. Once this influence is known, it is possible to determine the optimal frequency of the membrane surface regeneration, which provides the extremum of performance index.

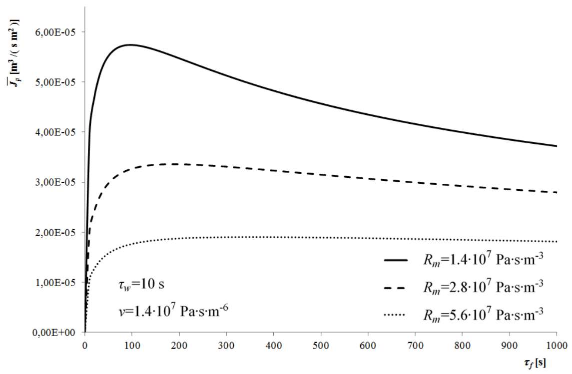

Fig. 2. The influence of the clean membrane resistance R_m on the optimal microfiltration duration in a single cycle τ_f, and on the optimal flux $\overline{J}_p$.

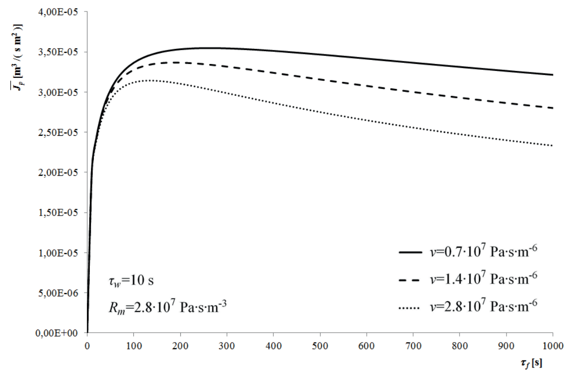

Fig. 3. The influence of the deposit resistance growth rate v on the optimal microfiltration duration in a single cycle τ_f and on the optimal flux $\overline{J}_p$.

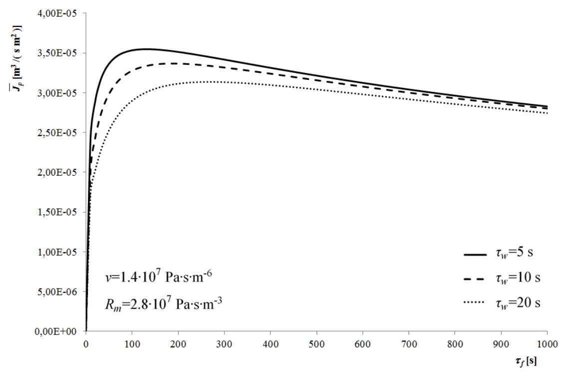

Fig. 4. The influence of the back washing time τ_w on the optimal microfiltration duration in a single cycle τ_f and on the optimal flux $\overline{J}_p$.

The analysis of the chart presented in Fig. 2 indicates that with the increase of the resistance of the clean membrane, R_m, the optimal flux, $\overline{J}_p$, decreases. It can be taken as obvious as the higher resistance means the lower productivity. With the increase of the resistance of the clean membrane, R_m, the optimal duration of microfiltration in a single cycle elongates. Thus, the optimal time of a cycle also increases, what corresponds to the membrane surface regeneration frequency decrease. It can be explained by the fact, that with the increase of the clean membrane resistance, R_m, the share of the deposit resistance in the overall resistance decreases, and thus there is no need to remove it so often. Nevertheless, regardless of the value R_m, optimal time periods of microfiltration during a single cycle, τ_f, are short and last no longer than 3 min.

The analysis of the chart presented in Fig. 3 shows, that with the increase of the deposit resistance growth rate, v, the optimal cycle performance, $\overline{J}_p$, decreases. It is also commonly accepted as the bigger average resistance of the deposit caused by its amount of increase, the lower productivity. With the increase of the deposit resistance growth rate, v, the optimal time of microfiltration during a single cycle shortens. Thus, the optimal time of a cycle duration also decreases, and thus the membrane surface regeneration frequency increases. Hence, the deposit characterized by the rapid resistance growth rate should be often removed. Additionally, it can also be seen in this case, that regardless of the value v, optimal time periods of microfiltration in a single cycle, τ_f, are short and do not exceed more than 3 min.

The analysis of the chart presented in Fig. 4 shows that with the elongation of the membrane surface regeneration time in a single cycle τ_w, the optimal flux, $\overline{J}_p$, decreases. The increase of the value, τ_w, makes the share of the unproductive membrane regeneration time increase in the total time of the cycle. It causes a decrease of the average productivity v. The increasing share of the unproductive time, τ_w, in the total time of the single cycle is reduced in the optimal time by the increase in time, τ_f. This, in turn, results in a decrease in the optimal membrane surface regeneration frequency. It all can be observed in Fig. 4. As in Figs. 2 and 3, Fig. 4 also points to a particularly important fact that the optimal time periods of microfiltration during a single cycle, τ_f, is short and lasts no longer than 3 min, which means that the optimal membrane regeneration frequency is high.

In summary, it can be concluded that the frequency of the membrane surface regeneration should be greater than the one commonly used in practice.

The comparison of the permeate flux for the pseudo-continuous process with membrane surface renewal by back-pulse with the permeate flux for the process without surface regeneration is shown in Fig. 5. It covers the calculation results for the same data as in Fig. 2. The horizontal lines reveal pseudo-stability of the permeate flux for processes with membrane surface renewal at different membrane resistance, R_m. The level of these lines has been obtained as the maximum (optimum) of curves in Fig. 2. The curves in Fig. 5 present the instantaneous permeate fluxes for processes without membrane surface renewal. The equation, which describes the instantaneous permeate fluxes, can be obtained using Eq. (8), which could be adapted for the process without membrane surface renewal. Hence, filtration time, τ_f, in one filtration cycle should be replaced by chronological time, τ, and volume, V_f, by V. Differentiating Eq. (8), one can obtain:

$$Q_p(\tau) = \frac{dV}{d\tau} = \frac{\Delta P}{\sqrt{R_m^2 + 2v\Delta P\tau}} \quad (23)$$

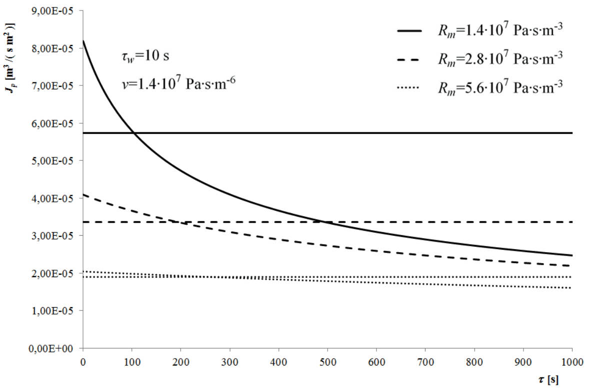

Fig. 5. Comparison of the permeate flux for the pseudo-continuous process with membrane surface renewal by back-pulse with the permeate flux for the process without surface renewal.

and next:

$$J_p(\tau) = \frac{1}{F}\frac{\Delta P}{\sqrt{R_m^2 + 2\nu\Delta P\tau}} \tag{24}$$

In Fig. 5, one can observe that in the initial step of the membrane process, an average permeate flux for the process with membrane surface renewal is smaller than for the process without membrane surface renewal. It is the result of losing a portion of the permeate for membrane back-washing. In the next steps of the process, the advantage of membrane renewal process is clearly visible.

5. Conclusion

The paper presents procedure of modeling and optimization of river water microfiltration purification in crisis conditions. The theoretical analysis enabled demonstrating that the most important task was to obtain maximum productivity. The considered process was a cyclical one. The duration of a cycle consisted of the time required for the permeate production, covering accumulation of contaminants on the membrane surface, and the time necessary for the membrane regeneration, connected with the loss of part of permeate for washing the membrane using the back pulse method. It was assumed that during the membrane regeneration, the membrane recovered its original state. Adoption of such the assumption corresponded to the identical character of all process cycles. Hence, the achievement of maximum productivity of the whole corresponded to the maximum performance of a single cycle. A dependence describing the average productivity of the cycle on the time of the permeate production in the cycle, in relation to other factors regarded as parameters, was derived. Such a study performance corresponded to the study of the influence of the membrane regeneration frequency on the average permeate flux. Values of all considered parameters were estimated. In calculations, data obtained for the commercial Liqui-Flux®W02 module were used.

The results showed that the optimal duration of a single cycle of microfiltration–regeneration of the membrane surface did not exceed 3 min. It was found to be much shorter than the cycle duration, which was commonly used in practice. Hence, the results indicated that the frequency of the membrane surface regeneration had to be greater than one commonly used in practice.

Nomenclature

F	—	Effective membrane surface area, m^2
J_p	—	Instantaneous permeate flux, $m^3s^{-1}m^{-2}$
$\overline{J_p}$	—	Average permeate flux during a cycle, $m^3s^{-1}m^{-2}$
p_1	—	Water pressure after the feed pump supplying river water to the membrane module, Pa
p_2	—	Pressure of permeate after the back pulse pump, Pa
ΔP	—	Transmembrane pressure, Pa
Q_p	—	Instantaneous permeate volumetric flow rate, m^3s^{-1}
$\overline{Q_p}$	—	Average volumetric flow rate of permeate obtained during a cycle, process productivity, m^3s^{-1}
Q_w	—	Flow rate of permeate for membrane washing, m^3s^{-1}
R	—	Current resistance of the membrane including the deposit, Pa s m^{-3}
R_m	—	Resistance of clean (fresh) membrane, Pa s m^{-3}
R_0	—	Current resistance of the deposit on the membrane, Pa s m^{-3}
R_{20}	—	Resistance of the membrane including the deposit after 20 min of microfiltration, Pa s m^{-3}
V	—	Permeate volume, m^3
V_f	—	Permeate volume obtained in time τ_f, m^3
V_w	—	Volume of permeate consumed for washing the membrane during a single cycle, m^3
V_{20}	—	Volume of permeate achieved within 20 min of microfiltration, m^3

Greek

τ	—	Time, s
τ_f	—	Time of microfiltration in a single cycle, s
τ_w	—	Time of membrane surface regeneration in a single cycle, s
τ_{20}	—	20-min time of microfiltration, s
ϑ	—	Proportionality factor introduced in Eq. (10)
ν	—	Deposit resistance growth rate, Pa s m^{-6}

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