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# Filtration Behaviors in Constant Rate Microfiltration with Cyclic Backwashing of Coagulated Sewage Secondary Effluent

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## ABSTRACT

The constant rate microfiltration characteristics of sewage secondary effluent pretreated with polyaluminum chloride (PACl) have been investigated. In order to reduce membrane fouling, the periodic operation of constant rate microfiltration and backwashing cycles was conducted using the fully automated experimental apparatus with the monolithic ceramic membrane module. As filtration proceeded, cake formation occurred on the membrane surface, causing an increase in pressure drop. Backwashing could reduce the flow resistance that resulted from the formation of the filter cake. However, the initial pressure drop seemed to increase after each backwashing due to the irreversible pore blocking of

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the membrane. Based on the intermediate blocking law, a mathematical model has been developed to describe the pore blocking behavior. Using the model in combination with the filtration rate equation for the compressible cake, the energy consumption has been evaluated for the whole process. The experimental results were in good agreement with those calculated from the theoretical model. Optimum operational conditions for an energy efficient process were suggested based on analytical results. The reclaimed water is found to be free from microorganisms and can be reused in applications such as toilet flushing or car washing.

*Key Words:* Constant rate filtration; Backwashing; Pore blocking; Cake formation; Microfiltration; Sewage secondary effluent.



## INTRODUCTION

Currently, considerable attention has been given to the concept of deriving beneficial uses from treated sewage secondary effluent through water reclamation. The inherent benefits associated with reclaiming treated wastewater for supplementary applications prior to discharge or disposal include the preservation of higher-quality water resources, environmental protection, and economic advantages. It is believed that increased population and water requirement will lead to increased demands on water resources worldwide. The reuse of sewage secondary effluent is a low-cost alternative that has become viable through the development of tertiary wastewater treatment systems.

Recently, a number of studies[1] have been performed for the upgrading of sewage secondary effluent. In this regard membrane separation process is gaining popularity for its advantages such as compactness, potentially less chemical usage, and ease of automation. Perhaps the most important factor is that the membrane provides an absolute barrier to particles larger than its pore size, and thus bacteria-free effluent can be achieved regardless of the feed water quality. It is extremely important to study the performance of membrane separation in the purification of sewage secondary effluent. However, there is currently lack of information on controlling factors such as formation of filter cake and its compressibility and the mechanism of pore blocking in microfiltration of multicomponent sewage secondary effluent.

Microfiltration is generally defined to be the filtering of a suspension containing colloidal or fine particles with linear dimensions in the approximate range of 0.05 to 5 μm. In dead-end microfiltration the filtrate is forced to flow through membrane pores, and the pressure drop across the membrane serves as the driving force for the filtrate flow. Separation is accomplished by retaining particles at the surface of the membrane, leading to the formation of a cake layer. As filtration proceeds the retained particles build up with time. The driving force across the cake has to be increased constantly to keep the flow through the membrane constant. Moreover, the cake structure may undergo changes as a result of cake compression caused by the drag forces acting on the particles by the filtrate flow. This change in cake structure, in turn, may affect the filtration performance. The term semi-dead-end microfiltration is applied to a process in which the membrane surface clogged by the filtration operation is backwashed by reversing the flow direction at regular intervals in order to disrupt the filter cake formed on the membrane surface and recover the initial transmembrane pressure.[2] Although backwashing removes the particles from the membrane surface or pores to a certain extent, the initial transmembrane pressure after each backwashing increases gradually due to the irreversible pore blocking.

Various approaches[3–7] have been made to explain the pore blocking phenomena during dead-end microfiltration. Many attempts,[2,8–17] for instance, application of shear stress to membrane surface, backwashing, and backpulsing, have been made in order to predict optimal operating conditions and to overcome the problem of pore blocking.

The main intent of this study is to assess the performance of constant rate microfiltration with cyclic backwashing during the purification of sewage secondary effluent. Specifically, a series of constant rate filtration experiments are conducted using monolithic ceramic membrane systems to investigate characteristics of filter cake, pore blocking behavior, and energy consumption. Finally a mathematical model is developed to explain the pore blocking mechanism. Using the model in combination with the filtration rate equation of compressible cake, the energy consumption for the whole process is evaluated and compared with the experimentally measured data.

## EXPERIMENTAL

In this study, the sewage secondary effluent from Ueda Sewage Treatment Plant (Nagoya, Japan) is used as feed water. The facilities treat wastewater from part of the city's residential area using an activated sludge system in which unit operations such as bar screening, grit removal, aeration, microbial decomposition, and secondary sedimentation are performed. Finally it undergoes chlorination prior to being discharged to a nearby river.

The secondary effluent just before chlorination was used as feed water in our experiments.

The monolithic ceramic membrane with 19 tubular channels manufactured by NGK Insulators, Ltd. (Nagoya, Japan) was used in this research. The inner diameter of each tubular channel and the membrane length are 4 and 150 mm, respectively, providing a total filtration area of 358 $cm^2$. The nominal pore size of the membrane used is 0.1 μm.

The schematic layout of the experimental microfiltration apparatus used for this work is represented in Fig. 1. The feed water kept in the refrigerator at 278 K was pumped to the subtank in which pH was adjusted to about 6.8 by the addition of the sulfuric acid, and its temperature was maintained at 293 K by passing through the thermostat before flowing into the flocculation tank. In order to coagulate the fine particles in the feed water, a coagulant, polyaluminum chloride (PACl) containing 2 ppm-Al was added to the flocculation tank equipped with mixers. The feed water pretreated with PACl was then transported to the vertically placed membrane module by the gear pump.

Constant rate filtration experiments were performed under the flow rate $J_v$ of 2.8 m/d. The microfiltration apparatus operates in a semi-dead-end mode, with flow from inside to outside of the membrane. The pressurized water that passed through the membrane was collected as the filtrate. A part of the filtrate collected was used as the backwash fluid. Backwashing was conducted when the transmembrane pressure differential across the filter cake reached the preset value $\Delta p_{cf}$ of 30, 60, or 90 kPa, and it was carried out under the pressure

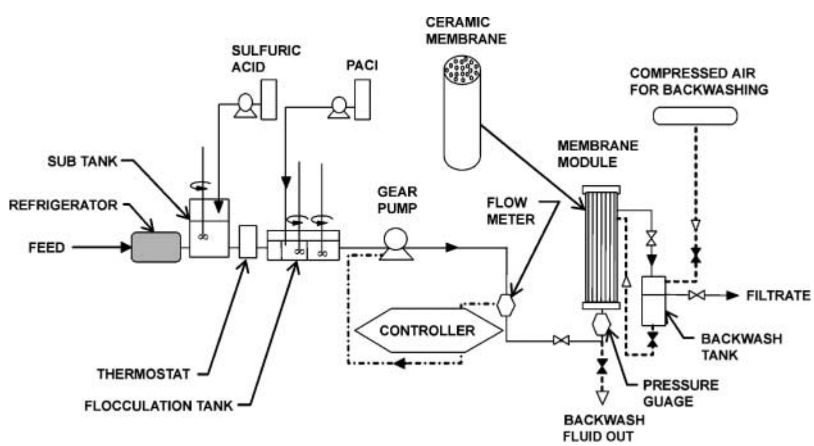


***Figure 1.*** Schematic layout of experimental apparatus.

***Table 1.*** Analysis methods of water quality.

| Category | Parameters | Methods |
|---|---|---|
| Solid | Turbidity | Transmitted-light turbidity (JIS[a]-K0101-9.2) |
| | SS | Suspended matter and evaporation residue (JIS[a]-K0102-14.1) |
| Organic | BOD | $BOD_5$ (JIS[a]-K0102-21) |
| | COD | $COD_{Mn}$ (JIS[a]-K0102-17) |
| Microbial | *E-coli* | Number of coliform group bacteria (JIS[a]-K0102-72.3) |

[a] JIS: Japan industrial standard.



of 500 kPa using 200 ml of the filtrate. The backwash time in one cycle is about 15 s. During backwashing, the reverse flow through the membrane removed the filter cake from the membrane surface. Cyclic operation was employed in which a period of forward filtration was followed by a period of backwashing.

During the experiments, the variations with time of the pressure drop $p$, pH, and the temperature were recorded in PC-based data acquisition system. Analyses of solid, organic, and microbial foulants present in the filtrate samples were conducted during the course of the experiment to investigate the performance of the microfiltration membrane. Water quality parameters were measured to assess each foulant group as follows: turbidity and SS for solids, BOD and COD for organics, and total coliform for microorganisms. Each of the water quality parameters was measured in accordance with specific methods as identified in Table 1.

## RESULTS AND DISCUSSION

### Quality of Filtrate

The analytical results of the feed and the filtrate are summarized in Table 2. The filtrate was found to be free of bacteria and can be used, without any further treatment, as reclaimed water for applications such as toilet flushing or car washing.

***Table 2.*** Quality of filtrate.

| Parameters | Feed | Filtrate |
|---|---|---|
| Turbidity (mg/l-kaolin) | 6 | <1 |
| SS (mg/l) | 1.5 | <1 |
| BOD (mg/l) | 3 | 1.3 |
| COD (mg/l) | 9.2 | 5.1 |
| *E. Coli* (counts per ml) | $1.7\times10^2$ | Nil |

## Variation of Pressure Drop

Figure 2 illustrates a typical result of pressure drop $p$, which is a direct measure of the flow resistance, vs. the filtrate volume $v$ per unit membrane area during the constant rate microfiltration and backwashing cycles conducted at $J_v$ of 2.8 m/d and $\Delta p_{cf}$ of 60 kPa. The filtration time in one cycle ranged from 5400 to 5700 s, whereas the backwash time was about 15 s. In each cycle, the rate of change of $p$ with $v$ increases gradually due to the formation of compressible filter cake. The backwashed membrane recommences each cycle at comparatively low initial pressure drop because the filter cake is exfoliated from the membrane surface. But this value tends to

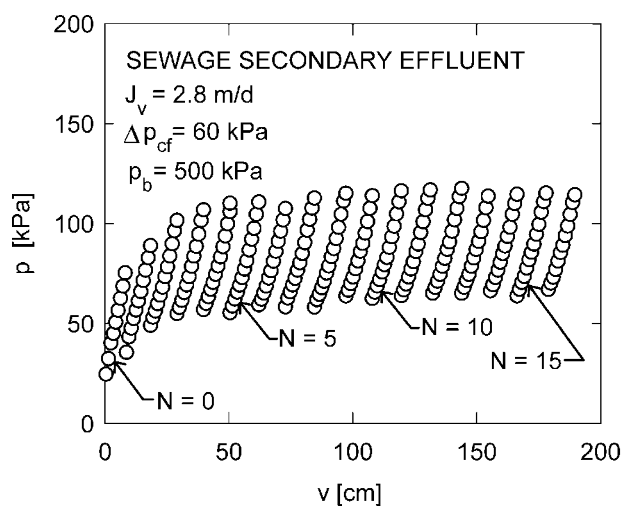


***Figure 2.*** Relation between pressure drop and filtrate volume during constant rate microfiltration and backwashing cycles.

increase with the number $N$ of cycles. This is probably because a part of fine particles present in the feed are irreversibly captured onto or into the membrane pores. It can be seen that as $N$ increases, the initial pressure drop across the membrane after each backwashing rises rather sharply during the first few cycles and gradually in the following cycles. By analyzing the experimental data, the characteristics of the filter cake such as the compressibility and the pore blocking mechanism can be investigated in detail.

## Analysis of Cake Formation

During production (filtration) operation, filter cake forms on the membrane surface. The build-up of the filter cake increases the hydraulic resistance to flow, thereby increasing the pressure drop across the cake markedly in constant rate filtration. Generally, the filtration rate $J_\mathrm{v}$ in the filtration period is related to the pressure drop $(p - p_\mathrm{m})$ across the cake by[18]

$$J_\mathrm{v} = \frac{1 - ms}{\mu \alpha_\mathrm{av} \rho s v}(p - p_\mathrm{m}) \tag{1}$$

where $m$ is the ratio of wet to dry cake mass, $s$ is the mass fraction of the solids in the slurry, $\mu$ and $\rho$ are the viscosity and density of the filtrate, respectively. The resistance $\alpha_\mathrm{av}$ is the average specific filtration resistance of the filter cake, $p$ is the pressure drop, and $p_\mathrm{m}$ is the initial pressure drop across the membrane after each backwashing. For moderately compressible materials it is possible to represent the resistance $\alpha_\mathrm{av}$ by power function of $(p - p_\mathrm{m})$ as follows:

$$\alpha_{av} = \alpha_0 (p - p_\mathrm{m})^n \tag{2}$$

where $\alpha_0$ is an empirical constant and $n$ is the compressibility coefficient. In constant rate filtration, the filtration rate $J_\mathrm{v}$ is constant. Thus $J_\mathrm{v}$ is related to the filtration time $\theta$ by the simple equation as

$$J_\mathrm{v} = v/\theta \tag{3}$$

Substituting Eqs. (2) and (3) into Eq. (1), one obtains

$$(p - p_\mathrm{m})^{1-\mathrm{n}} = \frac{\mu \alpha_0 \rho s J_v^2}{1 - ms}\theta \tag{4}$$

The above equation can be used directly to relate $(p - p_\mathrm{m})$ to $\theta$ for constant rate filtration.

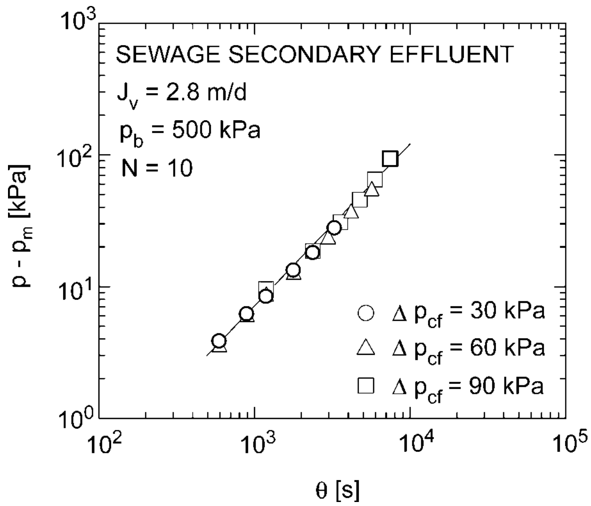


***Figure 3.*** Logarithmic plot of pressure differential across the filter cake against filtration time.

The experimental data at the cycle number $N$ of 10 for different values of maximum transmembrane pressure differential $\Delta p_{cf}$ across the cake are logarithmically plotted in the form of $(p - p_m)$ vs. $\theta$ as shown in Fig. 3. It is clear that regardless of $\Delta p_{cf}$ the variation of $(p - p_m)$ with $\theta$ can be approximated by a single straight line in accordance with Eq. (4). From the slope of the line, the compressibility coefficient $n$ was found to be 0.36, and thus the cake is moderately compressible.

## Analysis of Pore Blocking

Backwashing can remove most of the particles from the membrane surface or pores. However, irrespective of backwashing, the initial transmembrane pressure $p_m$ after each backwashing increases due to the irreversible pore blocking. The schematic diagram of the pore blocking mechanism is depicted in Fig. 4. In the first stage where the blocking takes place rapidly, let the number of open pores on a clean membrane at $N = 0$ be $x_0$. For $N < N_t$, let the number of clogged pores after each backwashing be $x$ and thus the number of the remaining open pores is $(x_0 - x)$ due to the irreversible pore blocking. In the second stage, pore blocking is assumed to

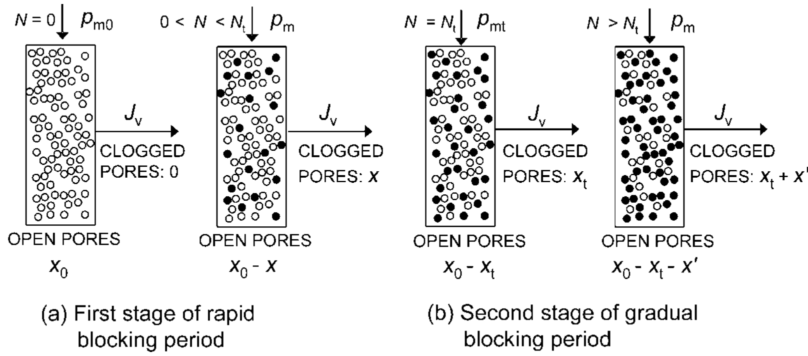


***Figure 4.*** Model configuration of pore blocking mechanism in constant rate microfiltration and backwashing cycles.

proceed more slowly. If the number of clogged pores at the transition cycle number $N_t$ is designated by $x_t$ then the number of open pores can be expressed as $(x_0 - x_t)$. Similarly for cycle numbers $N > N_t$ the number of open pores is given by $(x_0 - x_t - x')$. As a consequence, the constant filtration rate $J_v$ at $N = 0$ and $N = N_t$ can be respectively expressed as

$$J_v = kx_0 p_{m0} \tag{5a}$$

$$J_v = k(x_0 - x_t)p_{mt} \tag{5b}$$

where $k$ is a proportionality constant. Similar expressions for $J_v$ at $N \leq N_t$ and $N \geq N_t$ can be respectively written as

$$J_v = k(x_0 - x)p_m \tag{6a}$$

$$J_v = k(x_0 - x_t - x')p_m \tag{6b}$$

Assuming that pore blocking is a function of the frequency of backwashing,[8] the intermediate pore blocking model for the cyclic backwashing operation can be expressed in terms of cycle number $N$ as .[3−7]

$$x = x_0\{1 - \exp(-\eta N)\} \quad \text{at } N \leq N_t \tag{7a}$$

$$x' = (x_0 - x_t)[1 - \exp\{-\eta'(N - N_t)\}] \quad \text{at } N \geq N_t \tag{7b}$$

where $\eta$ and $\eta'$ are the empirical constants, showing the rate of pore blocking. Combining Eqs. (5a), (5b) and (6a), (6b) with Eqs. (7a) and (7b),

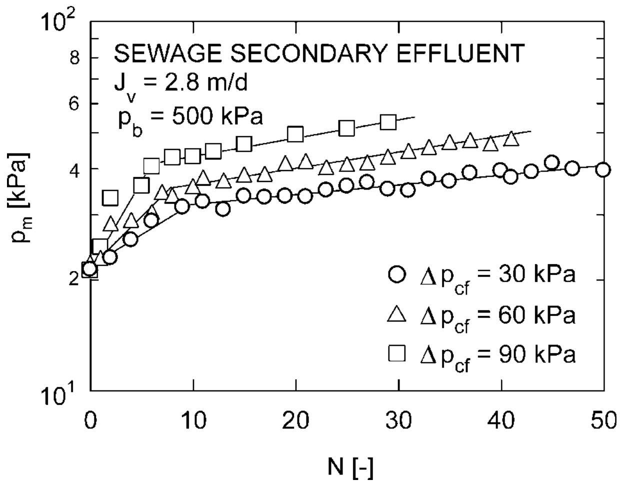


***Figure 5.*** Semi logarithmic plot of initial pressure against cycle number.

the variations of $p_m$ with the number $N$ of cycle can be obtained as

$$p_m = p_{m0}\exp(\eta N) \quad \text{at } N \leq N_t \tag{8a}$$

$$p_m = p_{mt}\exp\{\eta'(N - N_t)\} \quad \text{at } N \geq N_t \tag{8b}$$

In Fig. 5, the pressure drop $p_m$ is plotted against the cycle number $N$ for the different values of $\Delta p_{cf}$. As $\Delta p_{cf}$ increases, $p_m$ increases more rapidly with $N$, due to the migration of greater number of fine particles onto or into the membrane pores. From the slope of the fitted straight line of the experimental data, the values of the empirical constants $\eta$ and $\eta'$ in Eqs. (8a) and (8b) are determined, respectively.

Moreover, by introducing a variable $\gamma$ Eqs. (8a) and (8b) reduce to

$$p_m = p_{mi}\exp(\gamma) \tag{9}$$

where $\gamma = \eta N$ and $p_{mi} = p_{mo}$ for $N \leq N_t$, and $\gamma = \eta'(N - N_t)$ and $p_{mi} = p_{mt}$ for $N \geq N_t$. Figure 6 shows the relation between $p_m$ and $\gamma$. The plots can be approximated by a single straight line. Substituting the value of $n$ obtained from Fig. 3 and $p_m$ calculated from Eq. (9) into Eq. (4), the variation of pressure drop $p$ with time $\theta$ can be calculated for the whole process. In calculation, the experimental value of $N_t$ was employed.

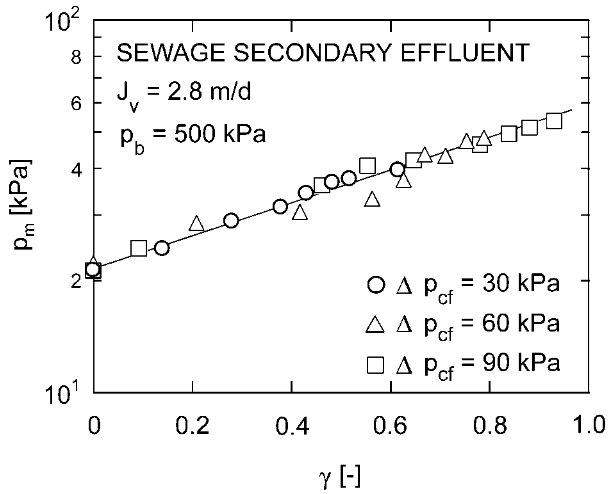


***Figure 6.*** Semi logarithmic plot of initial pressure against variable $\gamma$.

## Evaluation of Energy Consumption

In practice, from the point of view of the process efficiency it is quite essential to evaluate the energy consumption. Assuming that the frictional loss is negligible, energy $E$ required as driving force in filtration and backwashing to produce a net unit volume of filtrate can be calculated as

$$E = \frac{\int_0^v p dv + p_b v_b}{v - v_b} \tag{10}$$

where $p_b$ and $v_b$ are the backwash pressure and the volume of filtrate used as backwash fluid, respectively. Substituting $p$ calculated as stated in the previous section into Eq. (10) the energy consumption $E$ for various net filtrate volumes $(v - v_b)$ is calculated and compared with experimental data as shown in Fig. 7. An excellent agreement between experimental data and the predicted results shown by the lines is achieved for each $\Delta p_{cf}$, indicating the validity of the model proposed in this work.

Further calculations are carried out for higher $(v - v_b)$ values, and the results are plotted in Fig. 8. It can be observed that during the initial period of the operation the energy requirement for $\Delta p_{cf}$ of 30 and 60 kPa is nearly equal. However, as filtration proceeds the value of $E$ increases more sharply in the case of $\Delta p_{cf}$ of 30 kPa because of the higher energy loss incurred by more frequent backwashing. Rearranging the data shown in Fig. 8, the relation

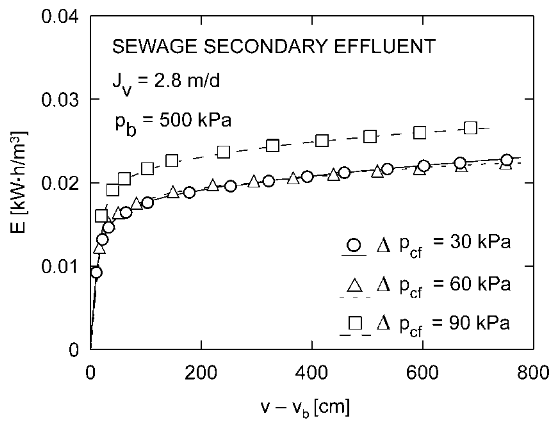


***Figure 7.*** Comparison between experimental and calculated data of energy consumption.

between energy consumption $E$ and $\Delta p_{cf}$ for different values of $(v - v_b)$ is evaluated as shown in Fig. 9. The most interesting feature of this result is that there exists an optimum $\Delta p_{cf}$ for each $(v - v_b)$. Furthermore, the information obtained from Figs. 8 and 9 can be used in the selection of process variables

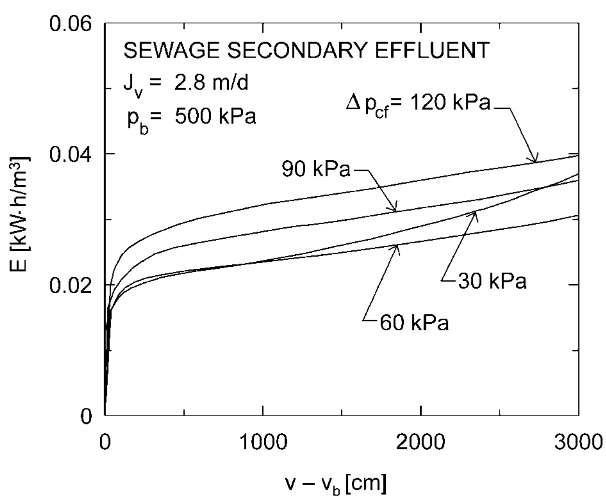


***Figure 8.*** Relation between energy consumption and net filtrate volume for various maximum transmembrane pressure differential.

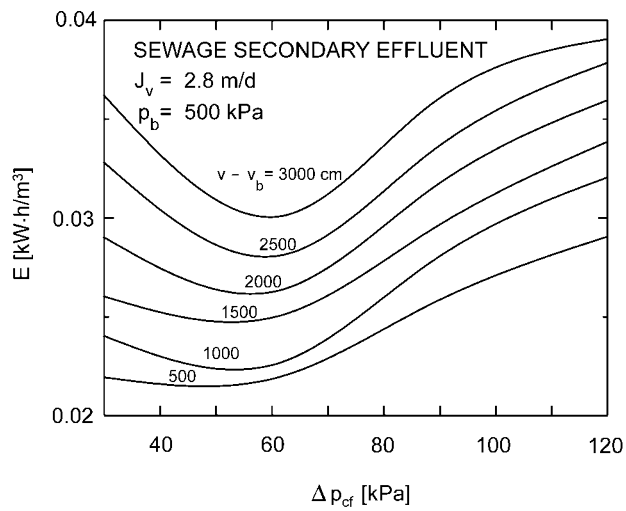


***Figure 9.*** Relation between energy consumption and maximum transmembrane pressure differential for various net filtrate volume.

such as $\Delta p_{cf}$ for the optimum backwashing condition in constant rate microfiltration with cyclic backwashing.

## CONCLUSIONS

The sewage secondary effluent was effectively purified by the semi-dead-end microfiltration system specially designed for this work. By combining the constant rate filtration theory for compressible filter cake with the two-stage pore blocking model proposed in this work, the energy consumption per net unit volume of the filtrate was evaluated based on the calculations of the pressure drop variations with time. Moreover, the method has been developed for determining the optimum operating conditions for energy efficiency. This work proved that the membrane separation process is a suitable technology for the purification of sewage effluent to be used as an alternative water source. Furthermore, the problem of life and cost of the membrane should be investigated by conducting the filtration experiments for longer periods.

## NOMENCLATURE

| | |
|---|---|
| $E$ | energy required for net unit volume of filtrate ($\mathrm{W \cdot h/m^3}$) |
| $J_v$ | filtration rate (m/s) |
| $k$ | proportionality constant defined in Eq. (5a and b) ($\mathrm{m^2 \cdot s/kg}$) |
| $m$ | ratio of wet to dry cake mass (—) |
| $n$ | compressibility coefficient (—) |
| $N$ | number of backwash and filtration cycle (—) |
| $N_t$ | number of backwash and filtration cycle at transition (—) |
| $p$ | pressure drop at time $\theta$ (Pa) |
| $p_b$ | backwash pressure (Pa) |
| $p_m$ | initial pressure drop across membrane after each backwashing (Pa) |
| $p_{m0}$ | initial pressure drop across clean membrane (Pa) |
| $p_{mt}$ | initial pressure drop across membrane at $N = N_t$ (Pa) |
| $s$ | mass fraction of solids in slurry (—) |
| $v$ | filtrate volume per unit membrane area ($\mathrm{m^3/m^2}$) |
| $v_b$ | backwash volume per unit membrane area ($\mathrm{m^3/m^2}$) |
| $x$ | number of clogged pores at $N < N_t$ (—) |
| $x'$ | number of clogged pores at $N > N_t$ (—) |
| $x_0$ | number of open pores at $N = 0$ (—) |
| $x_t$ | number of clogged pores at $N = N_t$ (—) |

*Greek letters*

| | |
|---|---|
| $\alpha_0$ | empirical constant defined in Eq. (2) ($(\mathrm{m}^{n+1} \cdot \mathrm{s}^{2n})/\mathrm{kg}^{n+1}$) |
| $\alpha_{av}$ | average specific filtration resistance (m/kg) |
| $\gamma$ | empirical constant defined in Eq. (9) (—) |
| $\eta$ | empirical constant defined in Eq. (7a) (—) |
| $\eta'$ | empirical constant defined in Eq. (7b) (—) |
| $\mu$ | viscosity of filtrate ($\mathrm{Pa \cdot s}$) |
| $\theta$ | filtration time (s) |
| $\rho$ | density of filtrate ($\mathrm{kg/m^3}$) |

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