



# Membrane fouling and cleaning in microfiltration of activated sludge wastewater

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## Abstract

A major obstacle in the widespread application of membrane microfiltration for activated sludge wastewater treatment is the rapid decline of the permeation flux with time as a result of membrane fouling. In this study, a hollow fiber membrane microfiltration unit was employed to treat two types of activated sludge wastewater of different particle size distributions. Theoretical models were used to fit the experimental flux data to identify the predominant membrane fouling mechanisms during microfiltration of each type of the activated sludge wastewater. A novel membrane cleaning method using sonication technique was evaluated. The performance of a combination of the various membrane cleaning methods, such as clean water backwashing, sonication, and chemical cleaning, was investigated. The results show that the main types of membrane fouling in microfiltration of activated sludge wastewater were attributed to initial pore blocking followed by cake formation. Periodic sonication of the membrane microfiltration module effectively removed the cake from the membrane surface and thus significantly recovered the permeation flux. However, sonication was not effective in flux recovery for membrane fouling caused by other mechanisms, such as pore blocking, and therefore the extent of flux recovery decreased with each sonication cleaning cycle. A combination of clean water backwashing, sonication and chemical cleaning with alkali and acid could achieve almost complete flux recovery. The underlying cleaning mechanisms and the effectiveness of each of the different cleaning methods to the different types of fouling are discussed.

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## 1. Introduction

The activated sludge process is commonly used in wastewater treatment for the removal of organic compounds. Conventional activated sludge processes usually consist of an aeration tank and a clarifier. The aeration tank is the place where organic breakdown and microorganisms' growth take place and the

clarifier is for the separation of the activated sludge from the decanted clear supernatant. The effluent quality from the clarifier is however susceptible to large fluctuations as a result of complications arising from abnormal microbial activities, such as bulking and foaming, occurred in the aeration tank [1], which makes separation (settling) of the sludge from water difficult. This has opened the area for membrane microfiltration to be increasingly used with the activated sludge process. With a membrane microfiltration unit replacing the clarifier, the rate of sludge–effluent separation is no longer limited by the settleability of the

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activated sludge, and, thus, a higher and more consistent effluent quality can be obtained [2,3]. A major factor against the application of membrane microfiltration with the activated sludge process is however the rapid flux decline due to membrane fouling.

Membrane fouling is characterized in general as a reduction of permeate flux through the membrane, as a result of increased flow resistance due to pore blocking, concentration polarization, and cake formation [2,4]. The effect of each of these fouling mechanisms on flux decline depends on factors such as membrane pore size, solute loading and size distribution, membrane material and operating conditions, etc. [2]. While the immediate effect of fouling is to cause a reduction in permeate flux, the long term effect may lead to irreversible fouling from microbial action on the membrane material and the reduction of membrane lifetime. To maintain the economic viability of a membrane process, membrane fouling has to be kept to a minimum. Researchers have devised various strategies to reduce membrane fouling and to improve membrane cleaning efficiency for flux recovery. These strategies include development of new membrane materials [5,6], new design of membrane module [2,3,7,8], modification of feed flow pattern [9,10], and incorporation of in situ or ex situ cleaning regimes in the membrane unit [11,12]. Sometimes, a combination of the various strategies may be employed in the same process [10,13].

For a membrane microfiltration unit treating activated sludge wastewater, biofouling is another major problem, arising from biofilm formation in the pores or on the surface of the membrane [14]. Biofouling may be initiated with the deposition of individual bacteria cells on the membrane surface and the cells subsequently multiply and form a biofilm. Biofouling is highly detrimental to membrane microfiltration since the unit is operated in biologically diverse and active environments with high solid loadings. It was reported that cellulose acetate membrane was biodegraded by activated sludge [15]. Biofouling destroys membrane structural integrity and leads to system failure, causing irreversible membrane damage and increasing the operational and maintenance costs.

Much work has been dedicated to study the mechanisms of microbial attachment and biofilm formation that precedes biofouling. In addition to the hydrophobic interactions between bacteria and membrane poly-

mer [16], researchers also suggest that extracellular polymeric substances (EPS) secreted by bacteria play an important role in bacterial attachment and biofilm formation [17,18]. EPS are composed of many organic compounds such as polysaccharides, amino polysaccharides and proteins [19,20] and are considered to aid in bioflocculation (floc formation) and enhance microbial attachment to membrane surface, preventing detachment by mechanically cross-linking and stabilizing the biofilm [21]. The EPS also acts as a diffusion barrier, retarding convective flow and transport of anti-microbial agent during membrane cleaning [18]. To prevent biofouling in membrane filtration, disinfectants [21,22] or other cleaning chemicals [23] have been used, together with physical methods such as air and liquid backwashing in order to fully recover the initial membrane flux.

The purpose of this research is to study the type of fouling mechanisms prevalent in membrane microfiltration treating activated sludge wastewater, and to examine the efficiency of various membrane cleaning methods to such membrane microfiltration unit. Two types of activated sludge wastewater were used to investigate the effect of particle size distribution and sludge floc characteristics on membrane performance and fouling. A novel membrane cleaning method using sonication was examined against other cleaning methods. Scanning electron microscopy, particle size distribution measurements, and experimental flux data fitting to different theoretical models were used to identify the types of membrane fouling mechanisms and their impact to membrane cleaning efficiency.

## 2. Theoretical models for membrane fouling

The permeation flux of particle-free water across a clean membrane can be described by Darcy's law as:

$$J = \frac{\Delta p}{\mu R_m} \quad (1)$$

where  $J$  ( $\text{m}^3 \text{m}^{-2} \text{s}^{-1}$ ) is the permeation flux,  $\Delta p$  (Pa) the transmembrane pressure (TMP),  $\mu$  (Pa s) the absolute viscosity of the water, and  $R_m$  ( $\text{m}^{-1}$ ) the hydraulic resistance of the clean membrane (or clean membrane resistance).

For suspension filtration, the permeation flux will always be lower than that given by Eq. (1). Flux

decline is a result of the increase of membrane resistance to the permeating flow, resulting from membrane fouling or particle deposition on or in the membrane. The mechanisms of membrane fouling usually include pore blocking, concentration polarization and cake formation [2,4,8]. For microfiltration, the fouling by concentration polarization may be negligible due to the large size of the particles retained [2]. Thus, the permeation flux through a microfiltration unit treating suspensions, such as activated sludge wastewater, can be given, by modifying Eq. (1), as:

$$J = \frac{\Delta p}{\mu(R_m + R_p + R_c)} \quad (2)$$

where  $R_p$  ( $m^{-1}$ ) is the resistance due to pore blocking, and  $R_c$  ( $m^{-1}$ ) the resistance arising from cake formation.

For microfiltration at a constant TMP, the initial permeate flux,  $J_0$ , will mainly depend on  $R_m$  as  $R_p$  and  $R_c$  are initially zero. With the proceeding of microfiltration operation, pore blocking and cake formation will cause  $R_p$  and  $R_c$  to increase, and change the relative significance of  $R_m$ ,  $R_p$ , and  $R_c$  in Eq. (2), and the microfiltration process can transfer from a membrane resistance-limited to a pore blocking resistance-limited or a cake resistance-limited process. According to Wiesner et al. [4], the permeation fluxes under each of these case may be given as:

$$\text{membrane resistance-limited : } J = \frac{J_0}{1 + J_0 K_m t} \quad (3)$$

$$\text{pore blocking resistance-limited : } J = J_0 \exp(-K_p t) \quad (4)$$

$$\text{cake resistance-limited : } J^2 = \frac{J_0^2}{1 + J_0^2 K_c t} \quad (5)$$

Eqs. (3)–(5) can be rewritten in a linearized form as:

$$\text{membrane resistance-limited : } \frac{1}{J} = \frac{1}{J_0} + K_m t \quad (3')$$

$$\text{pore blocking resistance-limited : } \ln J = -K_p t + \ln J_0 \quad (4')$$

$$\text{cake resistance-limited : } \frac{1}{J^2} = \frac{1}{J_0^2} + K_c t \quad (5')$$

where  $K_m$ ,  $K_p$ , and  $K_c$  are system parameters relating to membrane resistance, pore blocking resistance, and cake formation resistance, respectively.

By fitting the models in Eqs. (3')–(5') to the experimental history data of permeation fluxes, the predominant membrane fouling mechanism at different stages of the microfiltration operation may be identified if the experimental data can be described by one of these models. Eqs. (3')–(5') can also be used to evaluate the effectiveness of various membrane cleaning methods in removing the different types of fouling. This can be done by fitting Eqs. (3')–(5') to the experimental data collected from each microfiltration run after the membrane unit was cleaned by a specific cleaning method, and then comparing the changes of the values in  $K_m$ ,  $K_p$ , and  $K_c$  obtained from the slope of the best-fitting straight lines for the microfiltration data before and after the membrane cleaning. A change in the value of  $K_m$ ,  $K_p$ , or  $K_c$  gives an indication that the corresponding type of membrane fouling is affected by the type of cleaning method.

### 3. Experimental

#### 3.1. Microfiltration system

The experimental setup is illustrated in Fig. 1. The activated sludge bioreactor was operated in a batch mode and the membrane microfiltration module, M1, was immersed into the bioreactor during the experiment. Table 1 shows the specifications of the hollow

Table 1  
Specifications of the hollow fiber membranes used in the microfiltration study

Type	Asymmetric hollow fiber MF membrane
Membrane material	PVDF
Surface chemistry	Hydrophobic
Nominal pore size ( $\mu\text{m}$ )	0.1
Fiber length (mm)	15
External diameter (mm)	1.3
Internal diameter (mm)	0.3
pH tolerance	1–10
Membrane module material	Stainless steel
No. of membranes in module	20
Total effective membrane surface area ( $\text{m}^2$ )	0.0122522

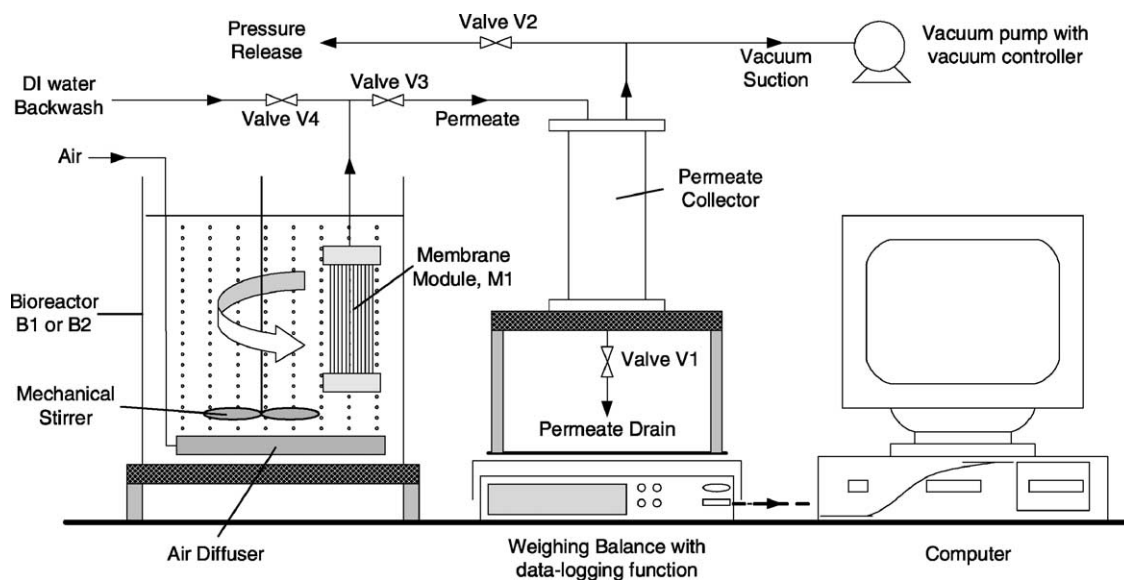


Fig. 1. Schematic diagram of the experimental microfiltration system treating activated sludge wastewater.

fiber membranes used in M1. During the operation of microfiltration, valves V1, V2, and V4 were closed and valve V3 was opened. Permeate was drawn from membrane module, M1, to the permeate collector, P1, by the vacuum suction generated by the vacuum pump (Buchi Vac V-500 with Buchi Vacuum Controller B-721) whose vacuum pressure can be digitally controlled. The permeate collector was placed on a weighing balance (Ohaus E1M210) and the weight readings of the accumulated permeate were transmitted to a computer and recorded at desired time intervals. After each microfiltration run, the system was stopped and the microfiltration unit was studied for cleaning performance by one, or more cleaning methods in sequence, for the recovery of the membrane permeability.

### 3.2. Activated sludge bioreactor

Two bioreactors with different activated sludge were used. Bioreactor B1 contained granular activated sludge with larger floc sizes while bioreactor B2 contained bulking activated sludge with smaller particle sizes. Raw activated sludge for both bioreactors was collected from the Jurong Water Reclamation Plant, Singapore. Bioreactor B1 was started one

year earlier than B2 to develop the granular sludge flocs.

The mixed liquor suspended solids (MLSS) for both bioreactors were maintained at about  $3500 \text{ mg l}^{-1}$  ( $\pm 200 \text{ mg l}^{-1}$ ) by discharging excess sludge, and the MLVSS/MLSS ratio in the system varied between 0.8 and 0.85. Nutrients were added on a batch basis to each bioreactor and the composition of the major nutrient sources in the feed is given in Table 2. The total  $\text{BOD}_5$  requirement was calculated on the basis of a  $F/M$  ratio of 0.05 per day. The stock solution was diluted by 10 times and then fed to the bioreactor within 1 h. The bioreactor was installed with a mechanical stirrer (IKA Labortechnik model RW-20DZN.n) to ensure thorough mixing of the contents. Air was supplied to the bioreactor through an air pump and the dissolved oxygen concentration in the wastewater was maintained at  $6.0 \text{ mg l}^{-1}$  ( $\pm 0.5 \text{ mg l}^{-1}$ ). The hydraulic retention time,  $\theta$ , of the bioreactor was controlled at 10 days.

Floc development in the bioreactor was monitored by examining the sludge samples from the bioreactor under a light microscope (Olympus BX60, Olympus Optical Co. Ltd., Japan, with Sony CCD-IRIS/RGB color video camera) and by measuring particle size distribution using a Multiparticle Sizer (Coulter

Table 2

Major nutrient sources in feed water to the activated sludge process (C:N:P ratio: 100:10:5)

Components in stock solution	Concentration in stock solution ( $\text{g l}^{-1}$ )	BOD <sub>5</sub> (stock solution diluted 100 times) ( $\text{mg l}^{-1}$ )	COD (stock solution diluted 100 times) ( $\text{mg l}^{-1}$ )
C source: Glucose, $\text{C}_6\text{H}_{12}\text{O}_6$	48.6		
N source: Ammonium sulphate, $(\text{NH}_4)_2\text{SO}_4$	8.8	490	790
P source: Tri-Potassium phosphate, $\text{K}_3\text{PO}_4$	6.5		

**LS230).** Sludge settleability was measured by the sludge volume index (SVI). The pH of the wastewater in the bioreactor was in the range of 6.5–7.5, controlled by using sodium bicarbonate as the buffer.

### 3.3. Membrane cleaning

Several membrane cleaning methods were investigated in the experiments, including backwashing with de-ionized (DI) water, sonication, chemical cleaning, and a combination of the various cleaning methods. Backwashing was performed in a flow direction opposite to microfiltration by forcing DI water through the hollow fiber membrane at a pressure of 2.5 bar for 15 min. Sonication was performed by sonicating the membrane module in a sonication bath (Cole Palmer 8891) at a frequency of 42 kHz and a bath temperature of 20 °C. Chemical cleaning was performed by drawing some cleaning chemical into the lumen of the membrane and soaking the module in each of the cleaning agent for 12 h. The sequence of chemical cleaning was alkali treatment of the module, followed by a brief rinse of the module with DI water, and then acid treatment of the module. The alkali used is a mixture of  $1 \text{ mol dm}^{-3}$  (1 M) NaOH and 0.05% sodium hypochlorite solution while  $1 \text{ mol dm}^{-3}$  (1 M)  $\text{HNO}_3$  solution was used for acid treatment.

To ensure that the condition and performance of the membrane module was almost the same in all experiments, post-cleaning was performed after every experiment to remove the fouling not removed by a specific cleaning method used in the experiments. This was done by soaking the module in an alkaline solution (the same as that used for alkali treatment in chemical cleaning) for 12 h. The membrane module was then backwashed with DI water for 15 min to remove the alkali and any unclogged material from the interior of the membrane. The module was then soaked in an

acidic solution for 12 h (the same as that used for acid treatment in chemical cleaning), and was backwashed again with DI water for 15 min. The effectiveness of the post-cleaning operation was evaluated by measuring the clean water flux to determine the degree of initial flux recovery. The extent of irreversible fouling was minimized to <5% of the flux reduction.

## 4. Results and discussion

### 4.1. Microfiltration performance: effect of particle sizes

Fig. 2 shows the permeate flux decay patterns of membrane microfiltration treating the two different types of activated sludge wastewater. Flux decay rates

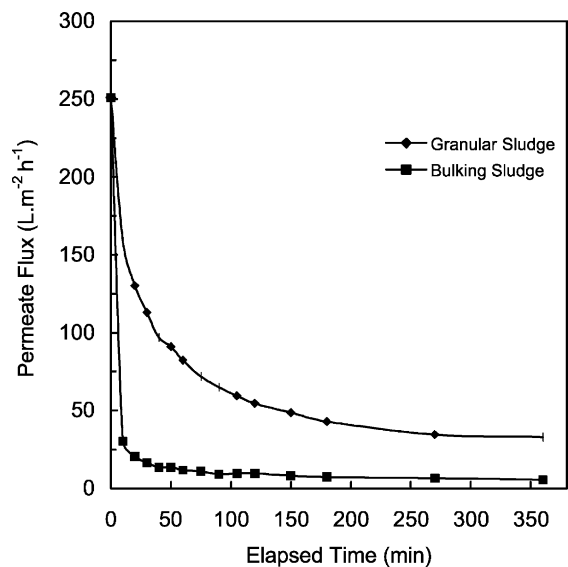


Fig. 2. Typical flux decay patterns of membrane microfiltration treating bulking and granular activated sludge wastewater.

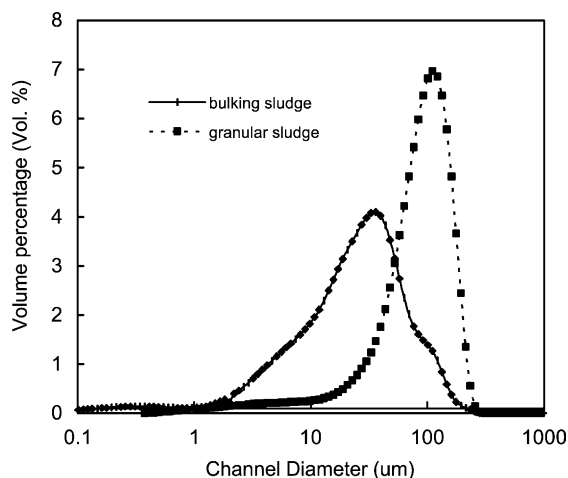


Fig. 3. Particle size distributions of the bulking and granular activated sludge wastewater.

were greatest at the beginning of each operation but approached zero at the steady state after 6 h. This indicates that fouling occurred rapidly once the membrane module was put into operation. The permeation fluxes for the granular activated sludge wastewater were however significantly higher than those for the bulking sludge wastewater during microfiltration. The difference in the performance of membrane microfiltration may be attributed to the differences in the particle size distributions of the two types of activated sludge wastewater. As shown in Fig. 3, the particle size distributions of the two types of activated sludge

wastewater were clearly different and the granular sludge had much greater particle diameters than the bulking sludge. The size differences of the two types of sludge observed under a light microscope were also very distinctive (see Fig. 4). Therefore, smaller particles can be concluded to cause more severe membrane fouling than the larger particles. It may be expected that particles of sizes close to or smaller than the membrane pore sizes can contribute to membrane fouling through internal and external pore blocking mechanisms [2,3]. In addition, cakes formed on membrane surface by smaller particles can be expected to create greater filtration resistance [24,25].

#### 4.2. Membrane fouling during microfiltration

As mentioned earlier, fouling mechanisms may be identified through fitting the various typical fouling models to the experimental microfiltration results. The ranges of experimental data that produce a straight line for each of the linearized fouling models in Eqs. (3')–(5') are presented in Fig. 5 for both the granular and bulking activated sludge. In general, microfiltration can be observed to follow an initial membrane-limited, and then a pore blocking-limited, and eventually a cake formation-limited process.

In the initial stage, the resistances  $R_p$  and  $R_c$  are small, and hence the clean membrane resistance,  $R_m$ , can exert a significant influence on the permeation flux (see Eq. (2)). As a result, the permeation flux may

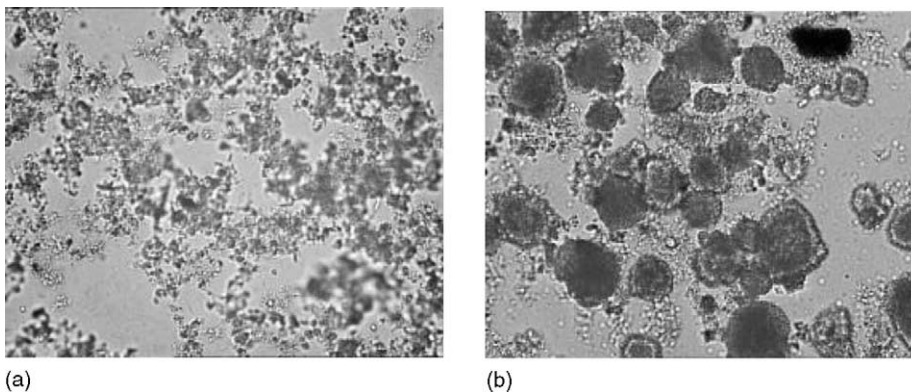


Fig. 4. Sludge particles observed under an optical microscope for the two types of activated sludge wastewater (bulking and granular). (a) Bulking sludge at 200 $\times$ , (b) granular sludge at 200 $\times$ .

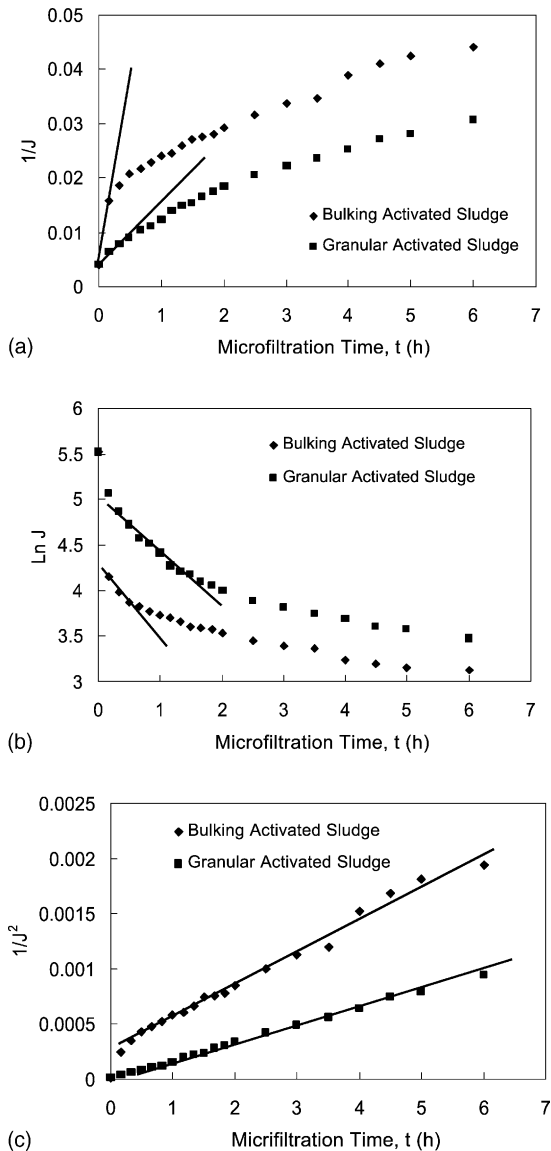


Fig. 5. Determination of fouling mechanisms from model fitting to experimental data (solid line indicates the fitted straight line). (a) Fitting of membrane-limited model, (b) fitting of pore blocking model, (c) fitting of cake fouling model.

be described by a membrane-limited model. However, due to the high solid loading, membrane-limited microfiltration lasted only a very short period of time, say 5–15 min or shorter, as shown in Fig. 5a. When particle deposition results in pore blocking, microfiltration becomes pore blocking-limited, described by

the straight lines in Fig. 5b. It is interesting to note that the pore blocking model is valid for a longer duration for granular sludge microfiltration than for bulking sludge microfiltration. Since more smaller particles in the bulking sludge approached the pores and resulted in pore blocking, the period of time for active pore blocking was therefore much shorter for the bulking sludge than for the granular sludge. It appears that the pore blocking mechanism has the most important impact on microfiltration permeation flux as, during this period of time, the permeation flux decay was rapid and significant (see Fig. 2). With more and more particles accumulated on the membrane, the process transitioned to a cake formation-limited process, which dominates the most part of a microfiltration operation run in the later stage, (see Fig. 5c). The greater gradient of the straight line for the bulking sludge is an indication of a higher cake resistance for cakes formed by the smaller particles. Cake formation does not seem to have as significant an impact on microfiltration flux decay as the pore blocking mechanisms since the permeation decay is relatively low during this period of time, in comparison with that in the pore blocking stage (see Fig. 2).

It should be mentioned that flux decay may be caused by several fouling mechanisms together, and the relative importance of each of the fouling mechanisms changes with time. This caused the transition of fouling mechanisms from one dominant form to another as shown in Fig. 5. The transition from pore blocking to cake formation fouling observed in this study is also in agreement with the observations of others [26,27].

#### 4.3. Membrane cleaning by sonication

Sonication involves the use of high energy, ultrasonic pulses to bombard and dislodge materials from surfaces. Sonication baths are commonly used to clean laboratory glassware with the principal function of scouring dirt and particles from surface of vessels. One physicochemical mechanism effecting the cleaning could derive from the high energy in the ultrasonic pulses that break bonds between vessel surface and adsorbed material. In research, sonication has been used to promote various aquatic reactions [28] and for dislodging bacterial biofilm for analysis of biofilm parameter [29]. Ozone and ultrasound had also been

used to reduce membrane biofouling by *Pseudomonas diminuta* from modified polysulfone membranes [30] where the effectiveness of dislodging the biofilm was found to depend on ultrasound intensity, cleaning frequency and distance from ultrasound transducer. In this study, the feasibility of using sonication for membrane cleaning was investigated. The microfiltration hollow fiber membrane treating the activated sludge wastewater from bioreactor B2 was cleaned using sonication at various sonication durations. The membrane microfiltration was operated for 1 h and then the membrane module was subjected to sonication for different durations. The operation and cleaning cycle was repeated to yield three consecutive sets of flux data for each of the sonication durations. The results are shown in Fig. 6.

Permeation flux increased significantly after the membrane was cleaned by sonication. This indicated that sonication is effective in reducing membrane fouling. However, a complete recovery of the initial flux was not achieved in any of the experiments. The initial flux continued to decrease after each sonication cleaning cycle. These results suggest that sonication is not effective in cleaning all types of fouling on the membranes. Table 3 shows the percentage flux recovery after each cleaning cycle with different sonication durations. The highest flux recovery was obtained with a sonication duration of 10 min. Further increase in the sonication duration did not improve flux recovery. It appears that longer sonication durations (15 and 20 min) reduced the percentage of flux recovery

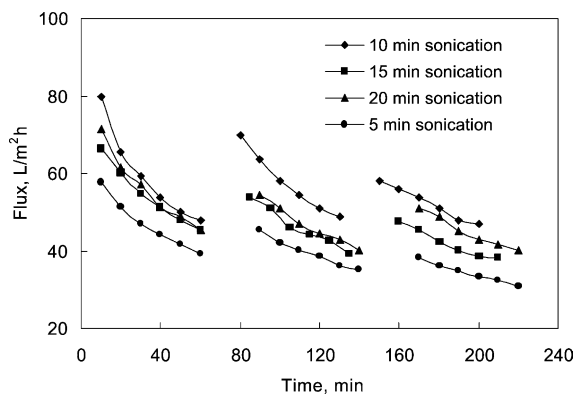


Fig. 6. Effects of sonication duration and sonication cycle on flux recovery (microfiltration of bulking activated sludge).

Table 3

Summary of percent flux recovery after each sonication cleaning cycle

Sonication duration (min)	Recovery in first sonication cycle (%)	Recovery in second sonication cycle (%)
5	76.8	66.1
10	87.5	72.5
15	80.6	71.6
20	76.1	71.8

and a shorter sonication duration (e.g. 5 min) was not efficient in cleaning the membrane. Particle size distribution measurements of sludge samples before and after sonication operation indicated that sonication caused breakage of particles in the cake and generated smaller particles that may enter the pores of the membrane and lead to pore blockage during sonication.

In Fig. 7, the typical results of the flux data from three consecutive microfiltration operations with a 20 min sonication duration in each cleaning cycle were fitted to the pore blocking and cake formation models for the bulking sludge. It is observed from Fig. 7a that the pore blocking parameter,  $K_p$  (the slope of the straight line), decreased after each sonication cleaning cycle (decreasing gradients), indicating that sonication cleaning has an influence on the pore blocking fouling mechanism. The activated sludge can be viewed as polydispersed particles and the value of  $K_p$  represent the average overall pore blocking rate by the particles. A reduction in  $K_p$  implies a reduction in the average pore sizes of the membrane and possibly, in the number of pores that are subjected to pore blocking. Since each sonication cleaning cycle caused a further reduction in the value of  $K_p$ , it could imply that some of the smaller particles created from the breakage of cake fragments plugged into the pores during sonication, reducing the available membrane area for pore blockage during microfiltration. In fact, the initial fluxes decreased after each cycle of microfiltration and sonication cleaning, i.e. from an initial value of  $70.71 \text{ m}^{-2} \text{ h}^{-1}$  in the first cycle to 50 and  $40.81 \text{ m}^{-2} \text{ h}^{-1}$  in the second and third cycles, respectively. Apparently, certain forms of fouling (at least pore blocking) were not effectively removed by sonication, which leads to the decline in the initial flux after each cleaning cycle. In contrast, the cake

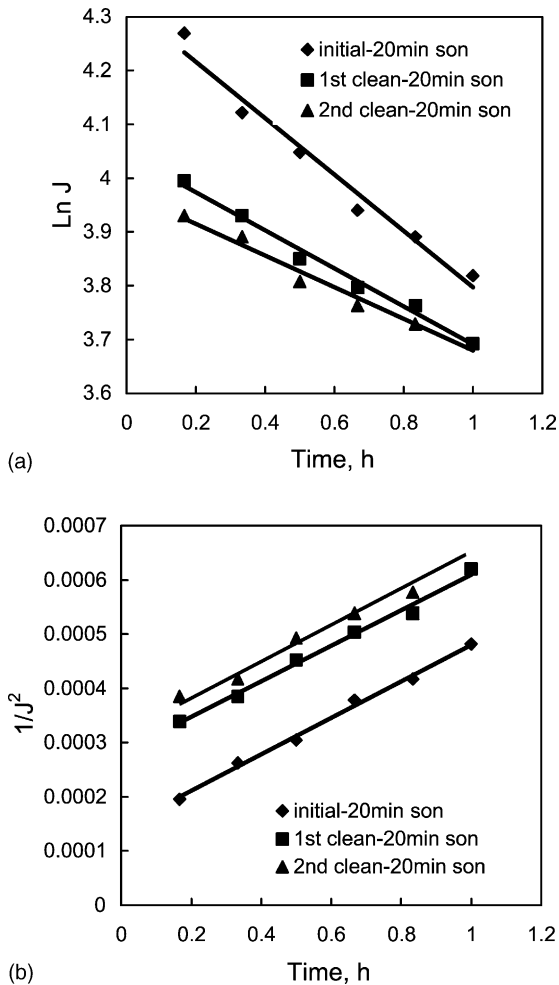


Fig. 7. Typical results of pore blocking and cake formation models fitted to the flux data from three consecutive microfiltration operations with a 20 min sonication cleaning (for the bulking sludge). (a) Fitting of pore blocking model, (b) fitting of cake formation model.

formation parameter,  $K_c$ , remained relatively unchanged after each sonication cleaning cycle (see Fig. 7b, the straight lines parallel each other and the slopes are the same). This indicates that sonication is effective in cleaning membrane with cake formation being the predominant fouling mechanism.

#### 4.4. Comparison of different cleaning methods

The efficiency of membrane cleaning by individual method of DI water backwashing, sonication, and

Table 4

Percent flux recovery by different cleaning methods

Cleaning method	Flux recovery (%)
Sonication (10 min)	60.8
Chemical cleaning	76.8
DI water backwashing	24.7
Combination cleaning	95.7

chemical cleaning, or a combination method (chemical cleaning, followed by sonication and then by backwashing) was evaluated by the recovery of permeation fluxes in microfiltration operation and the results are presented in Table 4. The results show that none of the individual cleaning method except the combination method recovered the initial permeation flux completely. DI water backwashing yielded a low flux recovery and appeared to be the least effective cleaning method.

In Fig. 8, the SEM images showing the surfaces of clean membrane, fouled membrane, and fouled membrane after being cleaned by sonication, chemical cleaning, DI water backwashing, respectively, and by the combination method are presented. New membrane surface is observed to be porous and free of particles (Fig. 8a). The surface of a used (fouled) membrane shows the presence of a cake layer (Fig. 8b). The cake layer was dense and non-porous in appearance, with rod-shaped bacteria and other materials. Sonication cleaning removed most of the cake and, as a result, most of the pores became open to the flow (Fig. 8c). The membrane surface was largely free of particles although it appeared to be less porous than the new membranes shown in Fig. 8a. The membrane surface after chemical cleaning still have much of the cake fragments on it (Fig. 8d), but the membrane was found to have a higher flux recovery than that cleaned by the DI water backwashing method, see Table 4. Chemical cleaning therefore may increase the permeability of the cake (biofilm) layer, without displacing the biofilm from the membrane surface. In fact, Flemming et al. [22] has reported that special chemicals such as some detergents could be used to modify the property of extracellular polymeric substances and increase the permeability of the biofilm (cake). Leslie et al. [17] also reported that certain chemical treatments could enhance the heterogeneity and porosity of biofilm

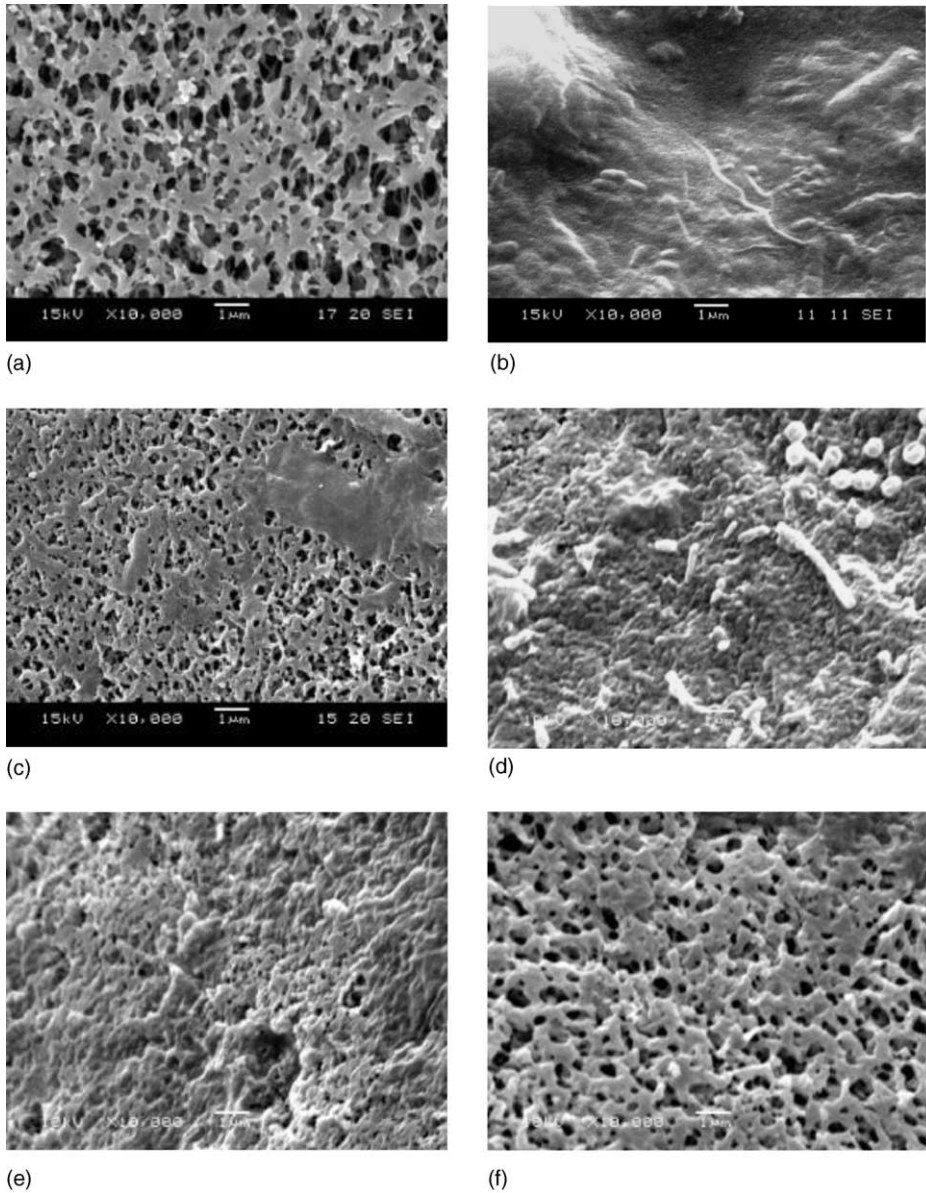


Fig. 8. SEM images showing the surfaces of clean membrane, fouled membrane, and used membrane after being cleaned by sonication, chemical cleaning, DI water backwashing, respectively, or by the combination method. (a) New membrane surface, (b) fouled membrane, (c) membrane cleaned by sonication, (d) membrane cleaned by chemicals, (e) membrane cleaned by water backwashing, (f) membrane cleaned by combined cleaning.

without the loss of biofilm mass. These results seem to justify the high flux recovery amidst the present of cake fragments on membrane surface in Fig. 8d. After DI water backwashing, the surface of membrane was

still covered with cake (Fig. 8e), though some small pores can be observed. Hence, backwashing with DI water in this study was not effective in removing cake fouling, and, probably, pore blocking fouling as

Table 5  
Proposed cleaning mechanism effected by each cleaning methods

Cleaning methods	Cleaning principle
Sonication	Cake removal by breaking down cake into smaller fragments, over-sonication may result in greater pore blocking
Backwashing	Drives out loosely attached particles in pores and slough attached biofilm (cake)
Chemical cleaning	Hydrolysis of organics molecules, loosen particle and biofilm (cake) attachment to membrane
Combination cleaning	All above

well, for microfiltration membrane treating activated sludge wastewater. The combination method appears to be the most effective method in membrane cleaning (see Fig. 8f) and the membrane surface was relatively clean and porous. It may be inferred that chemical cleaning can contribute to the removal of the adhesive forces that bound the biofilm to the membrane pores and surface (or destroy the biofilm structural integrity and weaken the biofilm–membrane adhesion), sonication method loosen and remove the cake, and DI water backwashing enhance the removal of loosened cake and particles in the pores. Table 5 summarizes the proposed cleaning principles effected by each of the cleaning methods as deduced from this study.

## 5. Conclusion

Pore blocking and cake formation can be the dominant fouling mechanisms in microfiltration of activated sludge wastewater. Pore blocking fouling prevails in the early stage of a microfiltration operation, which causes significant decline of permeation fluxes with time. Particle size and size distribution plays an important role in pore blocking fouling of membrane and small particles cause much severer fouling than the larger particles (bulking sludge caused much greater fouling than granular sludge). Cake formation fouling dominates most part of the microfiltration operation in the later stage after the initial pore blocking mechanism. Cake formation results in slower permeation flux decay over time.

Sonication can be used to clean membrane effectively for fouling caused mainly by cake formation.

It appears that 10 min of sonication is an appropriate duration as shorter and longer sonication durations did not give improved cleaning. Sonication may cause pore blocking due to breaking particles on the membrane and facilitating them to enter the pores of the membrane, thus decrease flux recovery rate with increased number of cleaning cycles.

For microfiltration treating activated sludge wastewater, a combination cleaning method by chemical cleaning, sonication, and DI water backwashing together is most effective in recovering the permeation flux. Cleaning by DI water backwashing alone is found to be least effective, especially in removing the cake. Chemical cleaning with alkali and acid may help to weaken the adhesion of particles or cake to the membrane in the pores or on the surface, and improve the permeability of the cake, but chemical cleaning is not effective to remove particles or cake from the membrane. Sonication can loosen particles from the membrane and therefore remove the cake from the surface. Both chemical cleaning and sonication cleaning can be enhanced by DI water backwashing to remove the loosened material attached to the membrane surface or trapped in the membrane pores.

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