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침지식 중공사 정밀여과 분리막에서 무기혼합입자 여과에 대한 단계별 공기세정의 영향

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Effect of Step-aeration on Inorganic Particle Mixtures Filtration in a Submerged Hollow Fiber Microfiltration Membrane

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요 약: 침지식분리막 오염을 최소화하기 위한 두 가지 공기세정방식을 비교하였다. 연속적인 공기세정과 단계별 공기량을 증가시키는 방식을 연구하였다. 15분의 여과 중에 세정공기의 증가는 5분마다 단계별로 공기량을 증가시켜주었다. 모의여과 원수에 분말활성탄을 10 g/L 이하 그리고 카올린은 20 g/L 이하로 준비하였으며, 플럭스는 80 LMH로 하였다. 단계별 공기세정방식은 연속적인 공기세정 방식보다 분리막 오염억제에 효과적이었다. 추가적으로 주입된 응집제는 분리막 오염저감을 보다 향상시켰다. 연속적인 공기세정의 오염현상은 공경막힘과 분리막 표면에 지속적인 입자의 축적에 기인하였다.

Abstract: The goal is to compare two different aeration strategies for a pilot scale operation of submerged microfiltration with respect to the minimization of membrane fouling. A constant aeration (65 L/min) was examined parallel with a step-wise increase in airflow rate (40 to 65 L/min). The airflow rate was stepped to a higher rate every 5 min and the step-aeration cycles were repeated at regular intervals of 15 min. The comparative filtration runs were conducted with synthetic water containing powdered activated carbon (~10 g/L) and/or kaolin (~20 g/L) at a constant flux of 80 LMH. The extent and mechanisms of fouling in the microfiltration were identified by determining hydraulic resistance to filtration and the fouling reversibility after cleaning. Results showed that the step-aeration effectively alleviated fouling in the microfiltration of synthetic water compared to when using constant aeration. A substantial decrease in fouling was achieved by combining with coagulation using aluminum salts regardless of the aeration strategies. The constant aeration resulted in increased pore blocking likely due to increased accumulation of particles on the surface of membrane.

Keywords: *Step-aeration, Submerged hollow fiber microfiltration membrane, Powdered activated carbon, Kaolin, Fouling*

1. Introduction

Membrane separations have grown exponentially from a laboratory scale to an industrial process with considerable technical and commercial impact[1]. Potential applications include MBRs for wastewater, drinking water and organic/inorganic particles and reverse osmosis desalination[2-5]. Membrane fouling and concentration polarization are two major factors responsible for transmembrane pressure (TMP) increase and exert major influence on performance of membrane separation systems. Membrane fouling is gen-

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erally caused by physical deposition, adhesion of feed materials onto the membrane surfaces and pores, while concentration polarization is the buildup of solute concentration close to the membrane surface[6]. In general, fouling can be removed by hydraulic means such as air scrubbing, intermittent filtration and backwashing.

Periodic backwashing improves membrane permeability and reduces fouling, thus leading to stable hydraulic operating conditions. The reverse flow removes the particles that are reversibly deposited on or within the pores of the membrane, while the foulants are swept off the membrane via cross-flow. These actions subsequently reduce fouling and improve permeate flux over time[7-14].

Backwashing is effective for enhancing of permeate flux with or without internal fouling. However, the results also indicated that the recovered flux of a membrane fouled with backwashing after a long backwash was lower than that of a fouled membrane without backwashing, indicating that more internal fouling occurs when backwashing was used to periodically remove the external cake layer[7].

In a submerged membrane system, modules are directly submerged in the reactor and air is injected outside the membrane to reduce membrane fouling. Aeration can prevent the deposit formation on the membrane surface[16-20]. The principle of induced shear by aeration is reported as a major strategy in controlling concentration polarization and cake formation[21].

Recently, an intermittent or/and cyclic aeration mode results showed that membrane fouling was caused by the deposition of heterogeneous mixed liquor fraction on the membrane surface and are interrelated[22,23]. Therefore, at the lower aeration intensities, the fouling rates were higher for the higher concentration of suspension than those with the lower concentration of suspension due to the significant deposition of foulants. As well, a next increase in aeration intensity resulted in the drastic drop overall fouling rates under different aeration intensity conditions. The phenomenon can be explained by the fact that foulants caused possible lateral cake scouring

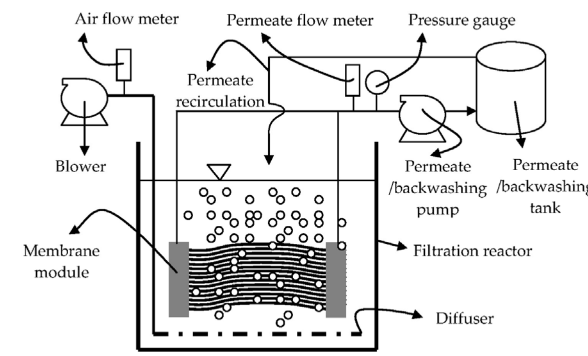

Fig. 1. Schematics of submerged membrane pilot plant.

action and formation secondary membrane under different aeration intensities. Nevertheless, the colloids still played a predominant role in the membrane fouling.

In this study, the fouling behaviors of submerged hollow fiber microfiltration membrane operated with different aeration modes were evaluated and a unique insight in heterogeneous mixed of the fouling layers. And their effect on the fouling hydraulic resistance was assessed. For this purpose, the fouling experiments were conducted applying two aeration mode that is continuous and step-aeration modes under constant filtration.

2. Materials and Methods

2.1. Membrane filtration reactor

The pilot scale submerged membrane reactor with a working volume of 270 L is shown in Fig. 1. The filtration tank was equipped with a submerged hollow fiber membrane module (Polyvinylidene fluoride, PVDF), with a surface of 20 m^2. The PVDF membrane used in this study (Kolon, Korea) has a nominal pore size 0.1 μm. The membrane module was horizontal type. Aeration was provided with an air flow rate up to 65 L/min through an air diffuser to limit fouling in the membrane module. The pump operated in forward and backward directions for the suction of permeate and the backwashing. Permeate from the permeate/backwashing tank returned to the filtration tank by gravity. A 100-L tank retained permeate for backwashing. Pressure gauge and flow meter were located at the permeate side of the membrane module to monitor TMP and flow rate continuously. Data acquis

Table 1. Operation Conditions Applied Runs

Run	Operating parameter for continuous filtration			
	Duration (s)	Interval (s)	Backwashing flux (LMH)	Constant flux (LMH)
[1)]CF		-		40 60 80

[1)]CF; Continuous filtration

Table 2. Operation Conditions Applied for the Different Aerations

Run	Operating parameter for continuous aeration and step-aeration modes		
	Duration (s)	Interval (s)	Aeration flow (L/min)
[1)]CA	-	-	50, 65
[2)]SA	300	900	From 40 to 65

[1)]CA; Continuous aeration
[2)]SA; Step-aeration

ition, control of the pump and blower were conducted with LabView (National Instruments, US).

2.2. Filtration test on model suspension

Fouling characteristics of submerged membrane module with kaolin (RC-15, US) and powder activated carbon (PAC) (Darco KB-B, Norit, Netherland) suspensions were investigated. Kaolin suspension was prepared from a tap water with the particle sizes ranging from 0.03 to 2.4 µm. Concentrations of the kaolin suspension were 1, 5, 10 and 20 g/L. PAC suspension was prepared from a tap water with the particle sizes ranging from 45 to 150 µm. Concentrations of the PAC suspension were 1, 3, 5 and 10 g/L. For the fouling test, lone suspension and binary of kaolin and PAC suspensions were used. Poly Aluminum Chloride (PACs, $Al_2(SO_4)_3 \cdot 18H_2O$) was used to dose coagulant at 0.5 g/L to flocculate kaolin and/or PAC.

2.3. Design of filtration and aeration mode experiments

Filtration was kept at constant flux applied at three fluxes during the continuous mode experiments without the relaxation and backwashing (Table 1). Two differ-

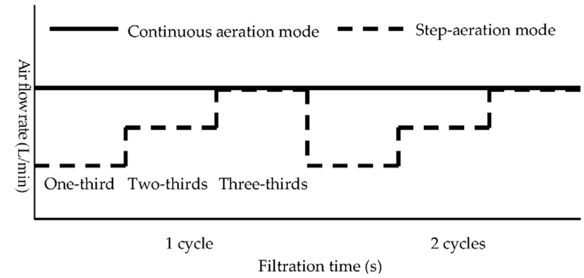

Fig. 2. Principles of two different aeration modes.

ent aeration for continuous and step-aeration (Table 2) were applied to the filtration experiments. Air flow rate was kept the same during continuous filtration mode for continuous aeration mode. A step-aeration mode featured 40 L/min of one-third, 50 L/min of two-thirds and 65 L/min three-thirds during the filtration cycle of 900 s (Fig. 2).

2.4. Hydraulic analysis of the membrane fouling

The intrinsic resistance of the membrane (R_m) (1.7×10^{11} m^{-1}) was tested by clean water tests, and the permeability of pure water was 480 LMH at 1 kg_f/cm^2 of a new membrane module. One of the basic models used for determining filtration resistance occurring during the permeate transport through porous membranes is Darcy's law :

$$J = \Delta P / \mu R_t \tag{1}$$

Where, J is the permeate flux ($L/m^2/hr$, LMH), ΔP is the TMP (kg_f/cm^2), µ is the viscosity of permeate (Pa · s), and R_t is the total filtration resistance (m^{-1}). After a filtration period, the fouled membrane was cleaned by a two-step protocol : (1) rinsed with tap water; (2) backwashing with a flux of 80 LMH with 50 L permeate water. By applying this protocol, the fouling layer could be separated into two fractions, i.e. rinsed (cake layer) and backwashing (pore blocking layer). The total hydraulic resistance was ascribed to these two fractions and the membrane (Eq. (2)) :

$$R_{total} = R_{cake} + R_{pore} + R_m \tag{2}$$

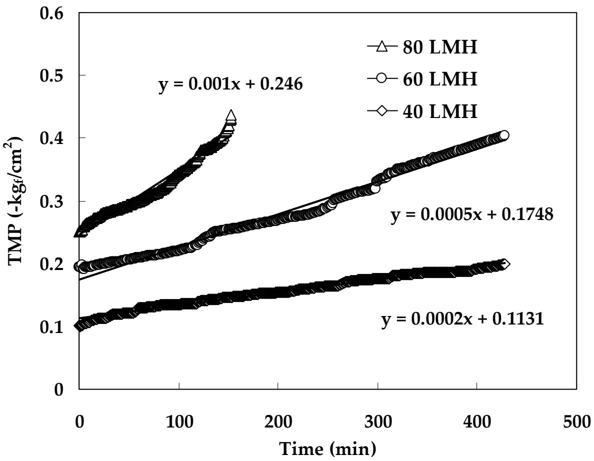

Fig. 3. TMP of different flux of kaolin 20 g/L (Continuous filtration and continuous aeration of 65 L/min).

After each step, the clean water test was applied to measure the remaining resistance.

2.5. Force on a deposited particle

The drag forces can be estimated with the stokes-equation. The drag force of the filtrate flow F_c is :

$$F_c = F_{stokes} \approx 3 \cdot \pi \cdot \mu \cdot x \cdot v_F \quad (3)$$

Where, x is the particle size (μm) and v_F is the filtration flux (m/s). The drag force of the crossflow is influenced by the wall-bounded shear flow. This results in a higher value of the drag force. According to theoretical and experimental investigations by Rubin[24] the drag force in a linear wall-bounded shear flow is 2.11 times higher than the calculated value by the Stokes equation. The diffusion force of the crossflow F_d is :

$$F_d = 2.11 \cdot F_{stokes} = 6.33 \cdot \pi \cdot \mu \cdot x \cdot w(x/2)$$
$$= 3.16 \cdot \pi \cdot \tau_w \cdot x^2 \quad (4)$$

Where, w is the crossflow velocity (m/s), τ_w is the shear stress (Pa). The deposition of the particles depends decisively on the hydrodynamic forces in the immediate vicinity of the membrane.

3. Results and Discussion

3.1. Continuous aeration mode with lone inorganic suspension

The effect of filtration flux was studied by varying the filtration flux in the range of 40~80 LMH. Typical result from the experiment is presented in Fig. 3. As expected, the initial transmembrane pressure (TMP) was generally proportional to the operating permeate flux. The fouling resulted in an increase in the TMP pressure during filtration time and no steady state was observed at all filtration. The different fluxes have different effect on membrane fouling. With a flux of 40 LMH, the TMP continued to increase slowly over 7.5-hr filtration. Relatively slower TMP increase rate is caused by the increase of the cake layer on the membrane surface. From this result it can be seen that the TMP was not very sensitive to the applied flux, but when the flux increased form 60 to 80 LMH, a significant effect of TMP was observed. When the filtration flux was increased to 60 LMH, the TMP sharply increased. The linear high TMP rate is caused by dense cake layer or pore blocking. A flux of 80 LMH accelerated membrane fouling. Furthermore, in the lasting period of 2.7-hr, the TMP increasing rate was 2 times of 60 LMH and 5 times of 40 LMH, respectively. The possible reasons for this phenomenon could be pore blocking and adhesion due to the rapid formation of a fine kaolin particle on the membrane surface. The TMP 'jump'[25,26] for the flux of 80 LMH occurred rather suddenly after 125-min of filtration and then exponential of TMP.

The variations of PAC concentration with step increments of TMP were studied at a flux of 40 LMH and air flow rate of 65 L/min. The simultaneous variations of TMP and PAC concentration with the time are shown in Fig. 4. The PAC concentration was first set at 1 g/L for 12-hr to obtain a stabilized TMP. The PAC concentration was then raised by 3, 5 and 10 g/L increments every 12-hr to the TMP stabilization. The TMP was PAC concentration independent. Fouling in this condition with PAC as the foulant particle has no

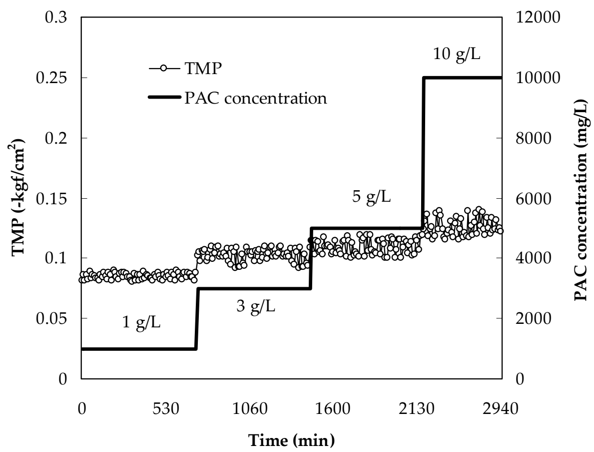

Fig. 4. TMP of different PAC concentration (Continuous filtration of 40 LMH and continuous aeration of 65 L/min).

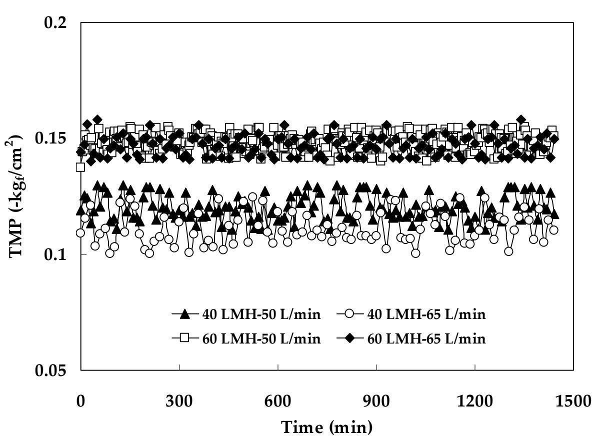

Fig. 5. TMP of different flux and air flow rate with PAC 10 g/L.

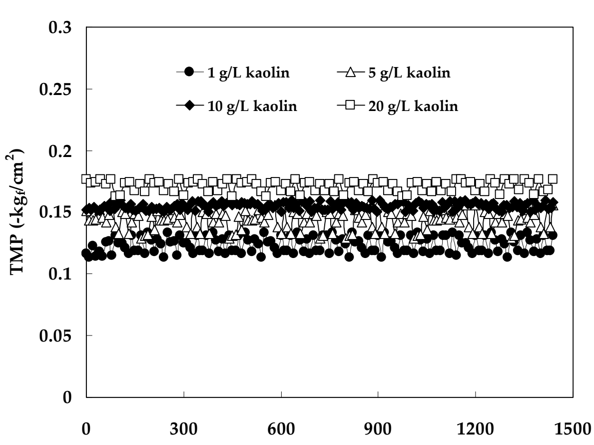

Fig. 6. TMP of different kaolin concentration based on PAC 10 g/L (Continuous filtration of 40 LMH and continuous aeration of 65 L/min).

effect. Reliable one reason may be that the low flux and high air flow rate conducted to stabilize TMP in this fouling experiment.

The TMP behavior can be explained in terms of the different flux and air flow rate as shown in Fig. 5. The initial TMP was generally proportional to the operating permeate flux. The effect of different flux and air flow rate on overall TMP was negligible for 10 g/L of PAC. Furthermore, applied two air flow rates may exert a limited effect on increase in TMP at two different fluxes. Periodic fluctuations in TMP were observed for a flux of 40 LMH applied at two air flow rate. In 40 LMH of flux, 65 L/min of air flow rate decreased the TMP than 50 L/min of air flow rate, indicating removal of some deposit. But, in 60 LMH of flux, increasing the air flow rate did not significantly improve performance, suggesting that PAC deposition did not readily affect membrane fouling.

3.2. Continuous aeration mode with mixed inorganic suspension

Fouling of mixed suspension with kaolin and PAC were studied at a flux of 40 LMH and air flow rate of 65 L/min. Fig. 6 shows the TMP with kaolin concentration 1, 5, 10 and 20 g/L under 10 g/L of PAC concentration. The observed fouling behavior during 24-hr filtration did not increase the TMP at all kaolin concentration. The initial TMP was highly proportional to increase in kaolin concentration. The particle size in the deposited matter was generally smaller, due to the lower deposition rate of the larger particles[27-30]. According to increase the amount of smaller particles, the smaller particles are more deposited. Moreover, these experiments were carried out up to 20 g/L of small particles. However, TMP did no increase during 24-hr filtration. At the different kaolin concentrations, PAC layer on the membrane demonstrated no resistance (Figs. 4, 5) with kaolin particle due to association with large particles PAC by shield effect[31]. Further, the deposition rate of mixed particles was due to difference in transport velocity. The mixed particles were limited to low constant flux and high air flow rate.

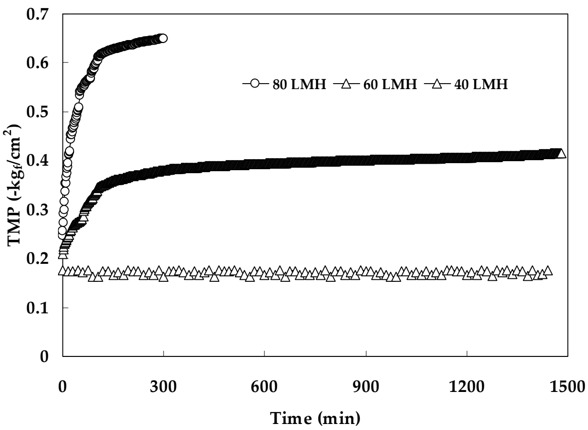

Fig. 7. TMP of different flux with mixed kaolin of 20 g/L and PAC of 10 g/L (Continuous aeration of 65 L/min).

Therefore, suggesting that the transport of large PAC particles toward membrane increased faster than small kaolin particles, that is, PAC particles interfered with moving to the membrane of kaolin particles.

Fouling of 20 g/L of kaolin and 10 g/L of PAC were studied at different fluxes of 40, 60 and 80 LMH with air flow rate of 65 L/min. Fig. 7 shows the TMP with flux of 40, 60 and 80 LMH, respectively. With a flux of 40 LMH, the TMP was very stable, no fouling was observed. When the flux was at 60 LMH, there was fast increase in the TMP for 2.3-hr but a steady state was observed over 24-hr filtration. For filtration at 80 LMH, although a sharp increase in TMP occurred in the initial stage for 2.3-hr, a steady state was eventually observed after about 2.7-hr. The steady state may be due to the effect of the cake layer on the membrane surface. In accordance with the increasing flux, the membrane surface increases the cake layer which then increased TMP. With increasing filtration flux from 60 to 80 LMH, filtration lasted only for 5-hr due to sharply increase of the TMP to 0.65 kg_f/cm^2. The TMP sharply increase at 80 LMH of flux, which possibly may cause increasing the transport of small kaolin particles toward membrane. Moreover, these kaolin particles deposited the cake layer more than blocks the membrane pores or dense cake layer on the membrane surface. The fouling was very sensitive to the flux increase in the range from 40 to 80 LMH.

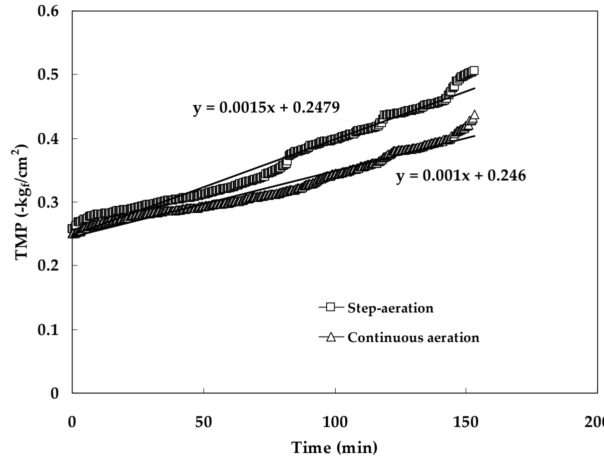

Fig. 8. TMP of different aeration modes for kaolin 20 g/L.

With increasing flux, kaolin particles may be more build-up on the membrane surface than PAC particles.

3.3. Step-aeration mode with kaolin suspension

Fig. 8 shows the TMP increase as a function of filtration time with continuous aeration (CA) and step-aeration (SA). In this experiment, the aeration mode was increased step by step and each step lasted for 300-s for step-aeration mode. A stepping-aeration mode featured a 40 L/min of one-third, 50 L/min of two-thirds and 65 L/min three-thirds during the filtration cycle of 900-s (Fig. 2). Air flow rate was kept the same (65 L/min) during the continuous filtration modes for continuous aeration mode.

The TMP of continuous mode represented in Fig. 3. The TMP of step-aeration mode in Fig. 8 showed that there are three distinct TMP stages over the whole filtration period. The first period lasting for about 1.3-hr, the TMP increasing rate is about 0.001 $kg_f/cm^2/hr$. Then, there was a sharp increase in very short time and the TMP profile transforms into the second period. The second period lasted about 1.4-hr, the TMP increasing rate was about 0.0014 $kg_f/cm^2/hr$. After this rapid increase of the TMP, it gradually transformed into the slowly increasing stage but lasting of filtration time was short than first stage. The third period lasting for about 0.35-hr, the TMP increasing rate was the similar to the second stage. After this rapid increase of

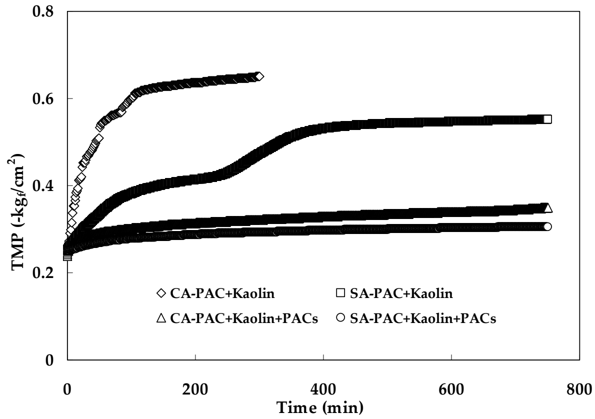

Fig. 9. TMP of different aeration modes with mixed kaolin 20 g/L, PAC 10 g/L and PACs 0.4 g/L (Continuous filtration of 80 LMH, continuous aeration of 65 L/min and step-aeration from 40 to 65 L/min).

the TMP, it sharply increased to the TMP to the end of experiment. The TMP increasing rate was 0.0015 $kg_f/cm^2/hr$. The fouling rate was 1.5 times higher than that of continuous aeration mode. With step-increase of the air flow rate, the fouling rate was much greater than that with continuous aeration. As well, initial low in air flow rate (40 L/min) resulted in the drastic increase in the overall fouling rate. When the air flow rate increased from 50 to 65 L/min, the fouling rate gradually increased especially through the TMP transition of four times. Although the above results indicate that the continuous aeration mode is much better than step-aeration mode, step-aeration mode still played a predominant role in membrane fouling. Furthermore, the deposition of small particles of kaolin in the membrane pore might result mainly from blocking due to the high filtration flux during initial aeration step period. And then, any additional deposition particles during the low aeration step period will be not effectively removed by subsequent high aeration rate. In previous result presented in Fig. 6, we confirmed that PAC particles removed to membrane fouling. Hence, we suggest PAC and coagulant such as PACs to be applied at kaolin only condition. PAC and PACs are expected to shield against kaolin and restrain the blockage of kaolin fine particles. Further, effects of the PAC and PACs in step-aeration are described of below.

3.4. Effect of different aeration modes on mixed suspension

The experimental results conducted at high flux of 80 LMH condition, are presented in Fig. 9. The TMP of continuous aeration mode with mixed 20 g/L of kaolin and 10 g/L of PAC suspensions was the most high among the TMP profiles. Continuous aeration was sharply increasing the TMP during short filtration time of 5-hr. This data is represented in Fig. 7. With step-aeration, 10 g/L of PAC dose could reduce the TMP increase which prevented pore blocking by kaolin of small particles. This is two stages over the whole operation period. In the first period, there is some rapid increase and the TMP profile transforms into the next period. Final stage lasting for 6-hr, the TMP is similar to steady state. In first period, the TMP increased blocking by the kaolin particles rather than cake layer. That is, PAC particles did not prevented kaolin of small particle in the membrane pore during the early filtration time. However, since the 6.5-hr of filtration time, the TMP increasing was at relative steady state. The presumption is that the deposition of PAC particles limited to kaolin of small particles. In other words, at the low aeration step, the deposition force was greater kaolin of small particle than PAC of large particle. As well, a second and third aeration step of more intense interrupted deposition of kaolin particles on the membrane pores.

PACs was applied to dose coagulant at 0.4 g/L to flocculate kaolin with continuous and step-aeration mode. 0.4 g/L of PACs was the best concentration for jar test to remove turbidity caused by kaolin particles. With PACs, the TMP increasing rate was dramatically lower than that without PACs. In continuous aeration mode, the TMP rate rapidly increased for 0.7-hr. Then, the TMP rate slowly increased to the end of filtration. On the other hand, with step-aeration mode, there was no rapid increase in the TMP rate for overall filtration but slow increased of TMP was observed over 1.7-hr. Then, a steady state was almost established at the end of filtration time.

Coagulation is a term used to describe the process of

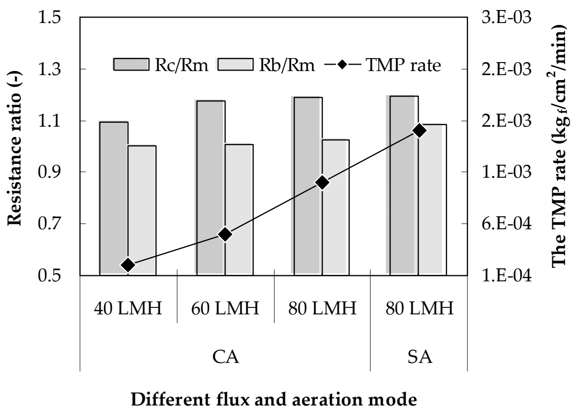

Fig. 10. Resistance ratio of different flux and aeration modes with kaolin of 20 g/L (Continuous filtration, continuous aeration of 65 L/min and step-aeration from 40 to 65 L/min).

aggregation of colloidal particles into large aggregates. When used in aeration membrane filtration, aim to reduce pore blocking of the membrane by depositing the colloidal particles and helping form sufficiently large aggregates to facilitate obtaining lower TMP rates. Coagulants can be applied either as a shield effect or as a mixture in the feed stream.

Muhammad et al.,[32] investigated the improvement of aeration microfiltration performance with coagulation for filtration of kaolin suspension. They concluded that, incorporating coagulation arrangement with aeration microfiltration would increase the particle size, which would tend to limit the increase of the deposit resistance and the TMP rate was very lower. This investigation of the process performance showed that, without coagulation, the TMP increase with respect to time was proceeding in an exponential form for early stage. The effect of coagulant on the TMP rate was obvious, particularly when both aeration mode was lower the TMP rate than without coagulant. With coagulation, membrane fouling might not be pore blocking but cake formation. Here, we suggested that, step-aeration leads to maintain the large aggregation of particles during the low air flow rate period. Therefore, with step-aeration mode, the fouling rate was lower than that with continuous aeration mode.

3.5. Hydraulic resistance of different aeration modes

To compare the continuous aeration and step-aeration modes on membrane fouling, the resistance ratio (R_c/R_m and R_b/R_m) is defined as the fouling contribution at cake (R_c) and pore blocking resistance (R_b) divided by that produced at a membrane resistance (R_m) with the different aeration mode. A lower resistance ratio indicates a lower fouling rate at the same aeration mode.

In kaolin filtration of 20 g/L with continuous aeration mode, when continuous flux increased from 40 to 60 LMH, R_c/R_m ratio increased, but R_b/R_m ratio was similar (Fig. 10). Then, at 80 LMH of flux, R_c/R_m and R_b/R_m ratio increased little than at 60 LMH of flux. The fouling mechanism with increased flux indicated that the fouling layer formed cake layer rather than pore blocking. However, in 80 LMH of flux, the TMP rate was much higher than flux at 40 and 60 LMH. The results suggested that applied air flow rate (65 L/min) might not remove the cake layer on the membrane surface with high flux of 80 LMH. In contrast, with step-aeration mode, when continuous flux of 80 LMH, R_c/R_m ratio was very similar that of continuous aeration mode, but R_b/R_m ratio was relatively higher than that of continuous aeration mode. Further, the TMP rate with step-aeration mode was 1.5 times higher than that of continuous aeration mode. Certainly, the dominant fouling mechanism in step-aeration was mainly pore blocking in the membrane pore due to the low aeration rate at every initial step period by step-aeration and high flux of 80 LMH. This results support our presumption that the fouling is not caused by single mechanism rather by more complex reaction.

In mixed kaolin and PAC of filtration with step-aeration mode, R_c/R_m and R_b/R_m ratio were significantly lower than that continuous aeration mode with and without PACs (Fig. 11). Further, comparing the effects on PACs, R_c/R_m and R_b/R_m ratio of step-aeration mode was dramatically lower with and without PACs conditions as well. The most of the low TMP rate was observed in step-aeration mode with PACs. With coagulant, membrane fouling reduced pore blocking rather

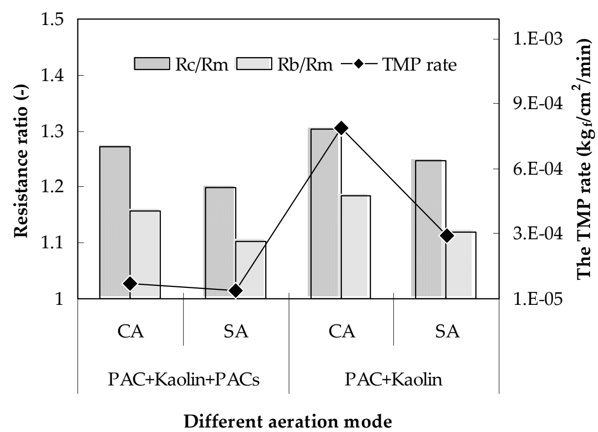

Fig. 11. Resistance of different aeration modes with mixed kaolin of 20 g/L, PAC of 10 g/L and PACs 0.4 g/L (Continuous filtration of 80 LMH, continuous aeration of 65 L/min and step-aeration from 40 to 65 L/min).

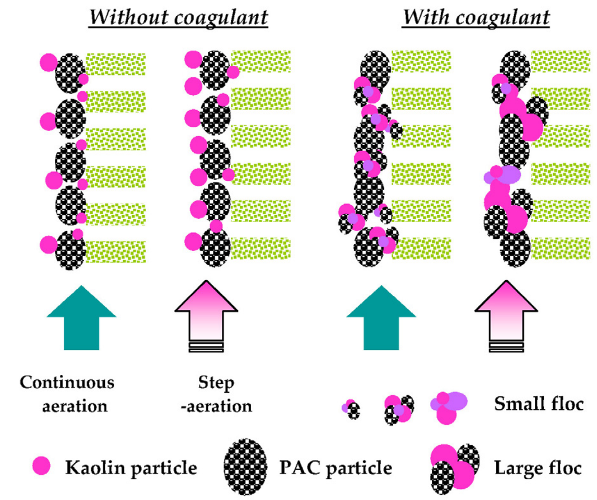

Fig. 12. Suggested fouling mechanisms of continuous and step-aeration.

than cake layer. Without coagulant in the experiments, PAC particles interfered attaching to the membrane with small particles of kaolin. Further, the transport of large PAC particles toward membrane increased faster than that of small kaolin particles during the low air flow rate period of step-aeration mode. Consequently, with step-aeration mode, pore blocking resistance was quite low in this study. However, with continuous aeration mode, the TMP rate was little higher than that with step-aeration mode due to maintain the large aggregation of particles during the low air flow rate period by stepping-aeration. Obviously, in this study, the TMP rate with step-aeration mode significantly alleviated with coagulant of PACs.

3.6. Proposed fouling mechanisms of different aeration modes

Based on the results presented in this chapter, fouling mechanisms for continuous and step-aeration mode is proposed (Fig. 12).

Without coagulant, a complex layer consisting of PAC and kaolin accumulates on the membrane surface. This can be verified by the sharply increase of TMP at the beginning (Fig. 9), which was caused predominately due to the pore blocking. First of all, kaolin particles attach on the membrane surface with continuous aeration mode. The main fouling mechanism is pore blocking (Fig. 11). Then, there was a sharp increase and the TMP profile transformed into the relative steady state by cake formation. Further, step-aeration can be verified by little increase in TMP at the beginning (Fig. 9), which was caused predominately due to the pore blocking. First of all, PAC particles was attach on the membrane surface. The main fouling mechanism was also pore blocking (Fig. 11). Then, there was a slow increase and the TMP profile transformed into the relative steady state by the first cake formation. Finally, the TMP rate was kept at relative steady state by the second cake formation.

With coagulant, a complex layer consisting of PAC, kaolin and aggregation flocs accumulates on the membrane surface. This can be verified by the some increase in TMP at the beginning (Fig. 9), which was caused predominately due to the cake layer by aggregation flocs. First of all, small size aggregation flocs or/and kaolin particles attach on the membrane surface with continuous aeration mode. The main fouling mechanism is cake formation (Fig. 11) by small size aggregation flocs caused by hindrance of continuous aeration mode. Then, there is a fast steady state and the TMP profile did not transforms. Further, in step-aeration, it can be verified by the stable TMP at the beginning (Fig. 9), which might be caused predominately due to cake formation by the large aggregation flocs. Over time, increase aggregation flocs size and the low air flow period resulted in a reduced pore blocking.

4. Conclusions

In this study, different aeration modes of filtration for inorganic particles were proposed. The aeration mode consists of two continuous aeration and step-aeration. Important conclusions could be drawn as:

Higher concentration of kaolin suspension strongly bound to the membrane surface with increasing filtration flux. It features a very dense structure and has very high TMP increase resulting in the highest densely compressed layer.

When PAC concentration was raised up to 10 g/L increments every 12-hr, TMP was very stable. The TMP indicated the PAC concentration independent in this experiment. Indeed, while reducing air flow rate to 50 L/min and increased flux to 60 LMH, the TMP rate showed the same result.

In the mixed kaolin and PAC, the fouling behavior during 24-hr filtration not increased at the TMP with kaolin concentration up to 20 g/L, based on PAC of 10 g/L. The PAC particles toward membrane increased faster than that of kaolin particles, that is, the PAC layer would continue to role as a prefilter.

In the mixed kaolin and PAC with high concentration, the TMP rate sharply increased at the beginning with increasing the filtration flux ranging from 60 to 80 LMH. Since the 2.3-hr of 60 LMH and 2.7-hr of 80 LMH, a steady state was maintained to the end of filtration. The steady state might be the cake filtration starting.

The effect of coagulant on the TMP rate was clear, particularly when both aeration modes were lower the TMP rate than that without coagulant.

With coagulation, membrane fouling might not be pore blocking but cake formation. Here, we suggested that, step-aeration leads to maintain the large aggregation of particles during the low air flow rate period. Therefore, with step-aeration mode, the fouling rate was lower than that with continuous aeration mode.

In kaolin only suspension, the dominant fouling mechanism in step-aeration was mainly pore blocking in the membrane pore due to the low aeration rate at every initial step period by step-aeration and high flux of 80 LMH. This results support our presumption that the fouling is not caused by single mechanism but more complex reaction.

The results in this study indicated that the TMP rate with step-aeration mode significantly alleviated coagulant of PACs. With coagulant, membrane fouling should be reduced pore blocking rather than cake layer. Without coagulant of the experiments, PAC particles interfered with attaching to the membrane of kaolin of small particles. With step-aeration mode, pore blocking resistance was quite low in this study. However, with continuous aeration mode, TMP rate was little higher than that with step-aeration mode due to large aggregation of particles during the low air flow rate period by step-aeration manner.

A mechanism was proposed to explain the fouling development for the different aeration modes. A PAC layer was quickly formed acting as a prefilter or a secondary dynamic membrane to entrap kaolin particles. During a step-aeration mode with coagulant, fouling proceeded very slowly. The deposited layer was not densely compressed, that is, remained loose and removable.

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