COMPARISON OF THE FILTRATION CHARACTERISTICS BETWEEN ATTACHED AND SUSPENDED GROWTH MICROORGANISMS IN SUBMERGED MEMBRANE BIOREACTOR

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Abstract—An attached growth bioreactor was designed to minimize the effect of suspended microorganisms on membrane fouling in submerged membrane bioreactor. Comparison of mixed liquor from attached and suspended growth systems was made to elucidate major factors giving rise to different filtration characteristics. Unexpectedly, the rate of membrane fouling of the attached growth system was about 7 times higher than that of the suspended growth system despite similar characteristics of soluble fraction from the two reactors. Filtration performance proved to depend on the concentration of mixed liquor suspended solids (MLSS). Better filtration performance with suspended growth was explained by the formation of dynamic membranes with suspended solids. A series of analyses such as hydraulic resistance, specific cake resistance, scanning electron microscope, and atomic force microscope were carried out to elucidate the different filtration characteristics of the two systems. © 2001 Elsevier Science Ltd. All rights reserved

Key words—submerged membrane bioreactor, suspended growth, attached growth, membrane fouling, dynamic membrane

INTRODUCTION

In wastewater treatment tighter controls on discharge limits have necessitated more elaborate and perhaps more expensive solutions than conventional biological treatment processes. One of the possible modifications of conventional biological treatment processes is the replacement of a secondary sedimentation tank by membrane units, which is called a membrane bioreactor (MBR). The use of MBRs in wastewater treatment is now emerging as an attractive technology with considerable advantages over conventional treatment methods (Arnot and Zahir, 1996; Chiemchaisri et al., 1993; Chiemchaisri and Yamamoto, 1994). However, by their nature as filters, membranes are prone to fouling as a consequence of interactions between the membrane and the mixed liquor, which reduces the filtrate flux and increases the required membrane area (Bouhabila et al., 1998), thereby deteriorating overall process performance.

Among theories proposed to explain flux behavior, a resistance-in-series model, which is based on the concept that the flux decline arises from a series of resistances, is generally used due to its ease of quantifying the degree of fouling. The cake resistance \( R_c \), one of the resistances cited in this model, has been reported as a main contributor to the total resistance \( R_t \) in MBR processes (Chiemchaisri and Yamamoto, 1994; Choo and Lee, 1996a,b; Chang and Lee, 1998; Kim et al., 1998; Chang et al., 1999; Lee, 1999; Park et al., 1999). The cake layer could consist of a variety of components: microorganisms and various inorganic and organic substances including extracellular polymeric substances (EPS).

A number of techniques have been explored in order to overcome membrane fouling due to the cake resistance \( R_c \). Those include backwashing, jet aeration, operation below critical flux, addition of coagulants, etc (Cote and Buisson, 1997; Howell, 1994; Ishida et al., 1993; Lee et al., 2000). Most of the studies have focused on minimizing the cake formation on the membrane surface, but few authors have tried to remove one of the primary sources of cake layer, which are the microorganisms suspended in the bioreactor. In this study, an attached growth system was designed in order to reduce the effect of suspended solids on membrane fouling. Most of the microorganisms were fixed on support media with...
only a negligible amount of microorganisms in the bulk. The filtration behavior and treated water quality were examined and compared with the suspended growth system and several analytical methods were applied to explain different filtration characteristics of the two.

MATERIALS AND METHODS

Experimental setup

Figure 1 shows a schematic diagram of the experimental setup for MBR. Two different experimental settings were designed for attached and suspended microbial culture systems, respectively, in order to compare the filtration performance between them. Detailed operating conditions are shown in Table 1. A U-shaped hollow fiber membrane module was immersed in the bioreactor having 5 L of working volume. Hollow fiber microfilters used were made of polyethylene with a pore size of 0.1 μm (Mitsubishi Rayon Co., Ltd., Japan). Aeration was done through diffusers at the bottom of the reactor to provide oxygen for biomass growth as well as shear to reduce cake formation at membrane surface. The bioreactors were put into a water bath to control the temperature at 25 ± 8°C. The membrane permeate was continuously removed by a peristaltic pump under a constant flux (25 L/m²/h), constantly monitoring the transmembrane pressure (TMP) build-up which indicates the extent of membrane fouling. The operation was stopped when the TMP reached 26 kPa because it was difficult to maintain the flux at constant level at TMP of over 26 kPa.

The feeding flow rate of synthetic wastewater was 15 L/d. The constant permeate flux was 25.0 L/m²/h, which is equal to the permeate flow rate of 40.4 L/d with the membrane surface area of 0.0673 m². Thus approximately 63% (25.4 L/d) of the permeate was returned to the reactor in order to keep the reactor volume constant. It was necessary to operate the systems at a comparably higher permeate flux than usual to see the effect of each experimental parameter on the system performance in a limited time in the laboratory. However, the permeate recycle to the reactor does not seem to affect the microbial conditions because the permeate originates from the reactor.

The membrane flux was calculated using an on-line computer connected to an electronic balance. All electric devices were connected to programmable logic controller (PLC, Master K10S, LG Industrial System, Korea) to automatically control the whole system. For attached growth (Fig. 2(a)), looped cord media (BioMatrix Technologies Inc., USA) of which the total surface area was 4.37 m² was immersed into the reactor at least for a month with continuous feeding of the wastewater prior to the operation of microfiltration. For suspended growth (Fig. 2(b)), all the experimental setup and operating conditions are exactly same as those with attached growth except the elimination of the looped cord media from the bioreactor.

The stock of synthetic wastewater was stored in a refrigerator and diluted with tap water before feeding. The composition of synthetic wastewater fed to the reactor is shown in Table 2. The main sources of carbon and nitrogen were glucose and ammonium sulfate, respectively. The ratio of COD:N:P in the feed was maintained at 100:10:1 with an influent COD concentration of 250 mg/L. Sodium bicarbonate was added as a buffer in order to control the pH of the mixed liquor in the range of 6.8–7.2.

Analytical methods

Mixed liquor suspended solids (MLSS) was measured according to the analytical methods described in the

Table 1. Operating conditions of submerged membrane bioreactors for both attached and suspended growth systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant flux (L/m²/h)</td>
<td>25</td>
</tr>
<tr>
<td>Maximum transmembrane pressure (kPa)</td>
<td>26</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>25</td>
</tr>
<tr>
<td>Air flow rate (L/min)</td>
<td>2.5</td>
</tr>
<tr>
<td>Working volume (L)</td>
<td>5</td>
</tr>
<tr>
<td>HRT (h)</td>
<td>8</td>
</tr>
<tr>
<td>Feed concentration (mgCOD/L)</td>
<td>250</td>
</tr>
<tr>
<td>Volumetric organic loading (kgCOD/m³/day)</td>
<td>0.75</td>
</tr>
<tr>
<td>PH</td>
<td>7.0 ± 0.2</td>
</tr>
<tr>
<td>DO (mgO₂/L)</td>
<td>6.1 ± 0.1</td>
</tr>
</tbody>
</table>

Fig. 1. Schematics of a submerged membrane bioreactor.
Standard methods (APHA, 1995). Mixed liquor pH was measured with a pH meter (Dong woo Medical System, Korea) and dissolved oxygen with a DO meter (YSI, USA). Chemical oxygen demand (COD) was determined by spectrophotometric method with DR 2000 (Hach, USA) instrument and total organic carbon (TOC) by TOC analyzer DC-180 (Rosemount, USA). Nitrate and ammonium concentrations were measured using ion selective electrodes and an autotitrator (Orion 940, USA).

To measure the amount of attached biomass on looped cord media, a sample of media was saturated with water at the start of the experiment, allowed to drip dry for 3 min and dried at 105 °C to measure the mass of the media. Every two days media samples were pulled from the reactor one by one to measure any change of the amount of biomass attached.

Protein and polysaccharide were analyzed by spectrophotometric methods; Dye-binding method was applied for protein analysis with Coomassie Brilliant Blue and BSA (bovine serum albumin) as a dye and a standard, respectively (Holme and Pect, 1983). For quantitative analysis of polysaccharide, the phenol–sulfuric acid method was used with glucose as a standard (Dubois et al., 1956). The molecular weight distribution of soluble organics was measured with gel permeation chromatography (GPC, Waters, USA). Polyethyleneoxide (SE-150, Tosoh, Japan) was used as a standard. Refractive index detector (RID, Waters R401, USA) and Shodex-Ohpak KB 802, 803 columns were used.

The cake layers of mixed liquor in the attached and suspended growth systems were visualized by scanning electron microscope (SEM) (JSM-35, JEOL, Japan) and an atomic force microscope (AFM) (Dimension 3000, Digital Instruments).

Characterization of major components of soluble organics

The oxidation states of organic molecules vary according to their chemical structures. Therefore, if the oxidation state of organic carbon is determined, rough estimation of the main substances in the sample solution could be made. If COD is expressed in mol O2/L and TOC in mol C/L, the “average” oxidation state of the organic carbon present can be obtained from equation (1) (Stumm and Morgan, 1981).

\[
\text{Oxidation state of organic carbon} = \frac{4(\text{TOC} - \text{COD})}{\text{TOC}}
\]  

(1)

In this context, soluble organics in the mixed liquor and on the membrane surface after filtration run were characterized by analyzing their oxidation states of organic carbons. Soluble organics in the mixed liquor was obtained with the centrifugation of the mixed liquor at 2000 g for 10 min and then second centrifugation of the supernatant at 10,000 g for another 10 min was given to completely remove microbial flocs and colloidal particles. The final supernatant was analyzed for the characterization of soluble organics in the mixed liquor. To analyze the organic substances on the membrane surface after filtration run, the membranes were placed in phosphate buffer solution and sonicated for 30 min. The buffer solution after sonication was centrifuged in the same way as described above. The final supernatant containing organic solutes was analyzed in terms of COD and TOC to calculate the mean oxidation state of organic carbon using equation (1).

Batch stirred cell filtration

In order to examine the characteristics of the cake on the membrane surface, batch filtration experiments were performed in dead-end filtration mode using stirred cell unit (Amicon 8200, USA). Hydrophilic PVDF (polyvinylidene difluoride) membrane with 0.22 μm pore (GVWP, Millipore Corp.) was used. The membrane surface area was 30 cm² and the operating pressure ranged from 10 to 110 kPa. Specific cake resistances were measured under unstirred conditions.

<table>
<thead>
<tr>
<th>Table 2. Composition of synthetic wastewater</th>
</tr>
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<tbody>
<tr>
<td>Composition</td>
</tr>
<tr>
<td>C₆H₁₂O₆</td>
</tr>
<tr>
<td>C₃H₇NNaO₄H₂O</td>
</tr>
<tr>
<td>(NH₄)₂SO₄</td>
</tr>
<tr>
<td>CH₃COONH₄</td>
</tr>
<tr>
<td>NH₄Cl</td>
</tr>
<tr>
<td>KH₂PO₄</td>
</tr>
<tr>
<td>K₂HPO₄</td>
</tr>
<tr>
<td>MgSO₄·7H₂O</td>
</tr>
<tr>
<td>FeCl₃·6H₂O</td>
</tr>
<tr>
<td>NaCl</td>
</tr>
<tr>
<td>CaCl₂·2H₂O</td>
</tr>
<tr>
<td>NaHCO₃</td>
</tr>
</tbody>
</table>

Fig. 2. Submerged MBR: (a) attached growth (MLSS: 100–2000 mg/L, attached biomass: 2000 mg/L) and (b) suspended growth (MLSS: 3000 mg/L) microorganisms.
The specific cake resistance was calculated using the slope of the plot of \(1/J^2\) vs. \(t\) from equation (2) and the compressibility of the cake layer was determined using equation (3) (Chudacek and Fane, 1984)

\[
\frac{1}{J^2} = \left( \frac{R_m \mu}{\Delta P} \right)^2 + \frac{2 \mu C_b \alpha}{\Delta P} \tag{2}
\]

\[
\alpha = x_0 \Delta P^a \tag{3}
\]

where \(J\) is the permeate flux, \(R_m\) is membrane resistance, \(\mu\) is the viscosity of permeate, \(\Delta P\) is the operating pressure, \(C_b\) is the MLSS concentration, \(\alpha\) is the specific cake resistance, \(t\) is filtration time, \(x_0\) is the specific cake constant, and \(n\) is the compressibility of the cake layer.

**Resistance analysis**

According to the resistance-in-series model the relationship between permeate flux and TMP can be given by (Choo and Lee, 1996a)

\[
J = \frac{\Delta P}{\mu R_t} \tag{4}
\]

\[
R_t = R_m + R_c + R_f \tag{5}
\]

where \(J\) is the permeate flux, \(\Delta P\) is TMP, \(\mu\) is the viscosity of the permeate, and \(R_t\) is total membrane resistance. \(R_m\) is the intrinsic membrane resistance. \(R_c\) is the cake resistance, and \(R_f\) is the fouling resistance due to irreversible adsorption and pore plugging.

Flux and TMP data are used to calculate resistances by equation (4); filtration of pure water with new membrane before operation gives \(R_m\) and \(R_t\) is calculated from the final flux and TMP values at the end of the operation. \(R_m + R_c\) is measured after removing the cake layer by washing the membrane with tap water after the operation followed by filtration of pure water. From these values each of \(R_t\), \(R_m\), \(R_c\), and \(R_f\) can be obtained using equation (5).

**RESULTS AND DISCUSSION**

The performance of MBR processes were studied using submerged hollow fiber membranes. Suction-type of microfiltration of the mixed liquor for the attached growth (Fig. 2(a)) and suspended growth (Fig. 2(b)) systems were carried out, respectively, in order to compare each other in terms of filtration characteristics and quality of treated water. Attempts were then made to find out factors affecting different filtration characteristics between the two.

**Treatment efficiency**

The submerged MBR system was operated at HRT of 8 h along with almost complete rejection of microorganisms for both systems. COD, NH\(_4\)–N, and NO\(_3\)–N concentrations in the permeate were monitored together with TMP variations during the system operation. In both systems, over 98% removal of COD and 95% removal of NH\(_4\)–N (Table 3) were achieved with the synthetic wastewater containing 250 mgCOD/L and 20.2 mgNH\(_4\)–N/L, showing that the treatment efficiency was in excellent levels irrespective of growth conditions.

**Filtration characteristics**

The increase rate of TMP is an important factor to evaluate the system performance in submerged MBR because it is directly related to the rate of membrane fouling.

The MLSS concentration in the suspended growth reactor was 3000 mg/L. On the other hand, the attached growth reactor contained only 100 mg/L of MLSS while 2000 mg/L of biomass were attached on the looped cord media. It was practically impossible to maintain MLSS concentration less than 100 mg/L even in the attached growth reactor because release of microorganisms off the cord media to the mixed liquor was inevitable. TMP was monitored under constant flux condition, and the operation was stopped when the TMP reached 26 kPa. In case of suspended growth system the TMP increased to 26 kPa after about 140 h of operation, while it took only 20 h for the attached growth system (Fig. 3). In other words, the increase rate of the TMP for attached growth was surprisingly 7 times higher than that for the suspended growth system. The attached growth system was originally designed to alleviate membrane fouling by removing the sources of cake

![Fig. 3. Variations of suction pressure during the submerged MBR operation of attached growth (MLSS: 100 mg/L, attached biomass: 2000 mg/L) and suspended growth (MLSS: 3000 mg/L).](image)

| Table 3. COD and ammonia removal efficiency in attached and suspended growth MBR |
|----------------|----------------|----------------|
|                | COD (mg/L)     | NH\(_4\)–N (mg/L) |
| Influent       | 250            | 20.2 (TN 23.9)   |
| Permeate       | Attached growth\(^a\) | Suspended growth\(^b\) |
|                | 99             | 98             |
| % removal      | Attached growth\(^a\) | Suspended growth\(^b\) |
|                | 0.99           | 0.17           |

\(^a\)MLSS: 100 mg/L, attached biomass: 2000 mg/L.
\(^b\)MLSS: 3000 mg/L.
layer, i.e. suspended solids and colloidal particles. However, contrary to expectations, membrane fouling proceeded much faster with the attached growth system than with the suspended growth although the latter had suspended solids 30 times higher than the former.

Other operating conditions being equal, the extent of fouling was believed to vary according to the mixed liquor composition in the bioreactor because membrane fouling should be the result of interaction between the mixed liquor and the membrane. The components of mixed liquor may be divided into two groups: (1) soluble fraction and (2) suspended solids including biomass and other colloids. Although the attached growth system was designed to minimize the effect of the latter, i.e. suspended solids, on membrane fouling, faster membrane fouling was observed with attached growth than that with suspended growth. In this context, soluble fraction, not suspended portion was thought to be more responsible for the membrane fouling in MBR. Consequently, comparison of soluble fraction of mixed liquor between the attached and suspended growth was made in order to explain such unexpected filtration characteristics.

Comparison of soluble organic compounds in mixed liquor

A bioreactor like an activated sludge tank contains a variety of soluble organic compounds, such as residual influent substrate and soluble microbial products (SMP). The term SMP has been adopted to define the pool of organic compounds that are released into bulk solution from substrate metabolism (usually with biomass growth) and biomass decay (Barker and Stuckey, 1999). Soluble compounds have been also reported to have larger fouling ability than suspended solids due to their interaction with the membrane material (Bouhabila et al., 1998; Wisniewski and Grasmick, 1998). Therefore, it might be suggested that the mixed liquors in the attached and suspended growth should contain different soluble compounds from each other, which would lead to different filtration behavior. Several features such as (i) molecular weight distribution, (ii) organic contents, and (iii) oxidation state of organic carbons in the mixed liquor for both attached and suspended growth reactor were examined.

In order to compare the molecular weight (MW) distributions, mixed liquor from each reactor was pretreated with 0.45 μm filter prior to GPC analysis. As shown in Fig. 4, both solutions contained various compounds with a wide distribution of MW from 0.1 to 400 kDa; MW < 1 kDa: 20–25%, MW 10–400 kDa: 40%. However, the attached and suspended growth bioreactors contained soluble organic compounds of quite similar MW distributions. TOC analysis was also adopted to characterize soluble organic contents. Two kinds of fractionation methods for mixed liquors, filtration and centrifugation, were employed to prepare analytical samples of soluble fractions because the definition of “soluble” compounds is still open to some debate. In the filtration method, a 0.45 μm filter was used to separate soluble organic compounds from the mixed liquor. In the other method, mixed liquor was first separated by centrifugation at 2000g for 10 min and the supernatant free of microbial flocs was centrifuged again at 10,000g for 10 min to further remove residual colloids. The supernatant obtained from the final step was used for TOC analysis. The TOC measurement showed that both attached and suspended growth reactors contained nearly the same amount of soluble organics regardless of the separation methods (Fig. 5(a)).

![Fig. 4. Molecular weight distribution of soluble organic compounds in mixed liquor for attached growth (MLSS: 100 mg/L, attached biomass: 2000 mg/L) and suspended growth (MLSS: 3000 mg/L).](image)

![Fig. 5. Soluble organic contents in mixed liquor for attached growth (MLSS: 100 mg/L, attached biomass: 2000 mg/L) and suspended growth (MLSS: 3000 mg/L): (a) total organic carbon and (b) protein and polysaccharide.](image)
EPS are soluble organic macromolecules that are a major fraction of soluble microbial products due to metabolism and cell autolysis (Wingender et al., 1999). The quantitative analysis of EPS was performed because EPS have been reported not only as major sludge floc components keeping the floc together in a three-dimensional matrix, but also as key membrane foulants in MBR system (Nagaoka et al., 1996). In this study, protein and polysaccharide concentrations were measured as they are known to be the main constituents of EPS. Protein and polysaccharide contents of soluble EPS in suspended growth reactor were slightly larger than those in the attached growth reactor (Fig. 5(b)). However, the difference in protein and polysaccharide quantity as well as their absolute concentrations (less than 1.0 and 1.8 mg/L each) was not so significant that it could be concluded that both systems contained similar species and quantities of EPS though they were in different growth conditions.

From the COD and TOC measurements the mean oxidation states of soluble organic carbons in attached and suspended growth reactors were calculated based on equation (1) and summarized in Table 4. Based on the calculated mean oxidation states, main constituents of organic compounds were roughly estimated according to Stumm and Morgan (1981). The mean oxidation states of 2–3 of organics in the mixed liquor corresponds to organic acids, suggesting that the major components for both systems had carbons in the form of organic acids which might be metabolic by-products or end-products of biodegradation. By contrast, as the mean oxidation states (−0.8 to −1.2) represents proteins and polysaccharides, they were presumed to be the major components of organic substances accumulated on the membrane surface, possibly due to their hydrophobic interactions with the membrane. Anyway, as the mean oxidation states of organics for both systems appeared to be almost the same in the mixed liquors as well as on the membrane surface it could be concluded that quantitative and qualitative characteristics of the soluble organic fractions in the mixed liquors did not vary according to the growth conditions. In summary, based on the series of examinations described above, the different filtration performance between two systems could not be attributed to the organic fractions in the mixed liquors. Consequently, we returned to the starting point and paid deeper attention to the suspended fraction instead of the soluble one.

**Mixed liquor suspended solids**

One of the clearest distinctions between attached and suspended growth systems should be the MLSS concentrations: the attached growth reactor contained only about 100 mg MLSS/L which corresponded to only 3.3% of the MLSS in the
suspended growth reactor (3000 mgMLSS/L). It was presumed that such difference might have brought about different filtration performance. In this context, further microfiltration experiments were carried out changing the MLSS concentrations in both attached and suspended growth systems in order to find out the effect of MLSS concentration on microfiltration characteristics. In all experiments, the attached growth reactor retained additional 2000 mg/L of biomass attached on the looped cord media immersed in the bioreactor. The MLSS concentration for the attached growth changed from 100 to 2000 mg/L, whereas it changed from 2000 to 5000 mg/L for the suspended growth system. The change in MLSS concentration was achieved by adjusting the sludge retention time (SRT) in the reactor without additional biomass input. MLSS was increased with increase in SRT. When MLSS reached the intended concentration, additional 2–3 times the SRT were required to achieve stable sludge condition prior to the filtration experiment. As shown in Fig. 6, the rate of membrane permeability loss (e.g., the rising rate of TMP) was retarded along with the increase in MLSS concentrations regardless of growth conditions, e.g., the higher the MLSS concentration, the slower the rising rate of TMP. For example, in the suspended growth system it took 75 h for TMP to reach 26 kPa at the MLSS of 2000 mg/L, whereas it took 260 h at the MLSS of 5000 mg/L. It was particularly interesting, however, that at the same MLSS concentration of 2000 mg/L, the two systems gave rise to almost the same filtration behavior; TMP reached 26 kPa after the almost same filtration time for both systems (70 and 75 h for attached and suspended growth system, respectively). From these experimental results, MLSS was thought to have been mainly responsible for the unexpected better filtration performance of the suspended growth system than that of the attached one.

Formation of a dynamic membrane by mixed liquor suspended solids

Suspended solids could be an important factor affecting membrane permeability because the suspended solids, mainly microbial flocs, in MBR could form a dynamic membrane on the surface of membrane. The conceptual illustration of dynamic membrane is shown in Fig. 7. Small particles like soluble organics will deteriorate the permeability of membrane by directly adsorbing onto the surface or inside the membrane pores when arriving at the membrane without any interruption (Fig. 7(a)). However, when large particles like microbial flocs are present (Fig. 7(b)), the deposit layer of microorganisms will accumulate on the membrane surface which is known as a dynamically formed membrane (Shoji et al., 1990; Holdich and Boston, 1990). Because low molecular weight substances or submicron colloidal particles could be rejected/sorbed and biodegraded by the dynamic membrane composed of living microorganisms (Yamagiwa et al., 1995), the dynamic membrane would provide small molecules with fewer chances of interaction with membranes and thereby alleviate the rate of membrane fouling. Also, the dynamic membrane may be removed from the membrane by the tangential air–liquid flow to the membrane surface because aeration was provided continuously in MBR. Repeated processes of formation and removal of dynamic membranes may slow down the loss of membrane permeability. However, it may be worth noting that aeration in submerged MBR may have some negative effects on membrane permeability because soluble or submicron particles can directly adsorb inside and block the membrane pores if dynamic membrane is removed by the tangential air–liquid flow.

Fig. 6. Filtration behaviors with varying MLSS concentration in attached and suspended growth bioreactor.

Fig. 7. Conceptual illustration of membrane fouling (a) without and (b) with dynamic membrane.
To prove the existence of dynamic membrane, the SEM images of membrane surfaces were investigated after filtration runs for attached and suspended growth systems. The membrane pores of a new membrane were clearly seen on the SEM image (Fig. 8(a)). While the surface of the membrane used for the suspended growth (MLSS: 3000 mg/L) reactor was covered with the microbial flocs and EPS layers (Fig. 8(b)), the membrane surface used for the attached growth (MLSS: 100 mg/L, attached biomass: 2000 mg/L) system was covered with some slime or gel layers (Fig. 8(c)), but not so significantly as that of the suspended system. AFM images provide some information on the roughness of the cake layer in each system. As shown in Fig. 9, the cake layer in the suspended growth was

![Fig. 8. SEM images of cake layer on membrane surfaces after filtration run: (a) new membrane (× 5,000), (b) used membrane for suspended growth (MLSS: 3000 mg/L, × 5,000), and (c) used membrane for attached growth (MLSS: 100 mg/L, attached biomass: 2000 mg/L, × 5,500).](image)

![Fig. 9. AFM images of cake layer on membrane surfaces after filtration run: (a) used membrane for suspended growth (MLSS: 3000 mg/L) and (b) used membrane for attached growth (MLSS: 100 mg/L, attached biomass: 2000 mg/L). a: root mean square.](image)
reconfirmed to be rougher than that in the attached one as could be expected from the SEM images, comparing the standard deviation of the height of each cake layer.

**Resistance analysis**

In this study, the attached growth system was originally designed in order to reduce the cake layer resistance ($R_c$) which has been known as a major contributor to the total resistance ($R_t$) (Chiemchaisri and Yamamoto, 1994; Choo and Lee, 1996a,b; Chang and Lee, 1998; Kim et al., 1998; Chang et al., 1999; Lee, 1999; Park et al., 1999). Resistance analysis was performed after filtration run in order to confirm any changes in various resistances by introducing attached growth system (Table 5). $R_m$, $R_c$, and $R_t$ were measured right after the TMP reached 26 kPa. It took 20 h for attached (MLSS: 100 mg/L, attached biomass: 2000 mg/L) and 140 h for suspended (MLSS: 3000 mg/L) growth to reach this TMP. In other words, the same total resistance was obtained about 7 times faster with attached growth compared with suspended growth. Small decrement in $R_c$ was observed in attached growth system compared to suspended growth, but still $R_c$ held a large part of $R_t$. However, decrease in $R_c$ was compensated with an increase in fouling resistance ($R_f$), which eventually led to severer loss of permeability in the attached growth system. These results revealed that soluble or colloidal particles as well as microorganisms in the mixed liquor could accumulate and form a secondary dynamic membrane on the surface of membrane, but without this the internal fouling would be severer. This is the reason why the $R_f$ value in the attached growth system is greater than that in the suspended one.

**Properties of cake layer on membrane surface**

Specific cake resistance is a parameter characterizing the cake layer formed on the membrane surface during filtration. Unstirred cell filtration was carried out to determine the specific cake resistances of cake layers in both attached and suspended growth system. The specific cake resistance ($z$) and the compressibility ($n$) of the cake layers were analyzed by changing the operating pressure in the range of 14–109 kPa and using equations (2) and (3). As shown in Fig. 10, the specific cake resistances in the attached growth (MLSS: 100 mg/L, attached biomass: 2000 mg/L) was one order of magnitude higher than that of mixed liquor in the suspended growth (MLSS: 3000 mg/L) through all the pressures tested. The compressibility of mixed liquor for attached (MLSS: 100 mg/L, attached biomass: 2000 mg/L) and suspended (MLSS: 3000 mg/L) growth were 0.79 and 1.08, respectively, indicating that the mixed liquor of suspended growth was more compressible than that of attached growth. As the cake layer in the suspended growth system contains more microorganisms, it may have higher compressibility. The low concentration of suspended microorganisms in the attached growth system could induce a lower compressibility of the cake layer. Also the AFM image of the cake layer of each system revealed

| Table 5. Effect of growth pattern on each resistance in the submerged MBR<sup>c</sup> |
|---------------------------------|----------------|----------------|----------------|----------------|
|                                 | Attached growth<sup>a</sup> | Suspended growth<sup>b</sup> |                  |                  |
|                                 | $10^{12}$m | %   | $10^{12}$m | %   |
| $R_m$                           | 0.49       | 12  | 0.50       | 12  |
| $R_c$                           | 2.94       | 69  | 3.39       | 80  |
| $R_t$                           | 0.81       | 19  | 0.35       | 8   |
| $R_t$                           | 4.24       | 100 | 4.24       | 100 |                  |
|<sup>a</sup>MLSS: 100 mg/L, attached biomass: 2000 mg/L.<br><sup>b</sup>MLSS: 3000 mg/L.<br><sup>c</sup>$R_m$, $R_c$, and $R_t$ were measured right after the TMP reached 26 kPa. It took 20 h for attached and 140 h for suspended growth to obtain the same total resistance of $4.24 \times 10^{12}$ m.<br><sup>d</sup>Fig. 10. Specific cake resistances of mixed liquors for attached and suspended growth.
rougher cake layer for the suspended growth system, which implicates loose packing of the particles and thus providing larger channels for the permeate flow (Fig. 9). These suggested that the mixed liquor of attached growth would have a higher fouling potential compared with that of suspended growth. However, when MLSS of 2000 mg/L existed in both attached and suspended growth reactors, little difference in both specific cake resistance and compressibility was observed demonstrating similar cake properties. It was a well expected result judging from the similar filtration behavior at the same MLSS concentration (Fig. 6).

CONCLUSIONS

In this study, two types of submerged MBR (attached and suspended growth systems) were compared with respect to various aspects in order to elucidate different filtration behavior from each other. The following conclusions could be drawn:

(1) The loss of membrane permeability proceeded more rapidly with the attached growth system than with the suspended one.

(2) Better filtration performance with suspended growth was attributed to the role of dynamic membrane formed on the membrane surface, which was confirmed by SEM and AFM images. This conclusion was drawn based on (i) the quantitatively and qualitatively similar properties of soluble organic compounds in mixed liquors for both systems and (ii) the improvement of membrane permeability with increasing in MLSS concentrations regardless of growth conditions.

(3) Better filtrability with the suspended growth could also be due to the rougher cake layer having smaller specific cake resistance than that with the attached growth.

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REFERENCES


