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Effect of heated aluminum oxide particles dynamic membranes on polymeric and ceramic microfiltration membrane

Kyung-Jo Kim, Am Jang*

Graduate School of Water Resources, Sungkyunkwan University, Jangan-gu, Suwon, Gyeonggi-do, 440-746, Korea, Tel. +82-31-290-7526, Fax +82-31-290-7549, email: amjang@skku.edu (A. Jang)

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ABSTRACT

Membrane fouling and resistance in drinking water treatment systems can be considerably reduced by precoating or predepositing the dynamic membrane (DM) filtration system using adsorbent particles on the membrane surface. The characteristics and roles of heated aluminum oxide particles (HAOPs) for adsorbent size and surface loading according to membrane type (ceramic: Ce; polymeric: Po) were investigated using ahumic acid (HA) solution. DM filtrations precoated with Ce or Po membranes indicate that fouling occurs in both membranes at the cake layer. In the case of Ce membrane filtration, the effect of foulants was noticeably reduced and irreversible membrane fouling can be alleviated by pretreating the Ce membrane with HAOPs. Permeability is proportional to the adsorbent size and surface loading. The optimum surface loading and particle size of HAOPs on the Ce membrane filtration should be <75 μm and 0.05 Al g/cm^2, respectively. Using a DM with HAOPs, membrane performance is more enhanced when using the Ce membrane than when using the Po membrane. From these results, it could be concluded that DM filtration with a Ce membrane has potential as an operating system for alleviating membrane fouling.

Keywords: Ceramic membrane; Dynamic membrane; Membrane fouling; Polymeric membrane

1. Introduction

Over the past few decades, Korea has reached higher levels of achievement concerning water supply systems. However, efforts to improve the water treatment efficiency are still needed and many investments have been made to achieve such improvement. The application of other physicochemical methods using membranes has created a specific new environmental issue in drinking water treatment systems. Natural organic matter (NOM) is one of the major contributors impeding low pressure driven membrane processes such as microfiltration (MF) and ultrafiltration (UF) for use in drinking water treatment systems. It is well known that NOM plays an important role in the occurrence of fouling and results in flux decline significantly below the theoretical capacity of membranes [1–6]. In general, the organic foulants in filtration systems are comprised of colloidal and particulate organic matters that commonly develop a gel cake layer on the membrane surface, blocking the pores [7–9]. Finding ways to avoid or reduce NOM has been a critical issue for decades for the successful application of membrane processes in water treatment. Although the organic foulants can be considerably reduced by several pretreatments such as coagulation, adsorption, ion exchange, and chemical oxidation [10–15], they occasionally cause rapid and often irreversible poor membrane performance [16–25]. For example, coagulation has a significant effect on the removal of the hydrophobic NOM fraction. However, previous studies indicate that the neutral hydrophilic fraction still contributes to irreversible fouling [26,27]. In addition, adsorption by polyaluminum chloride (PAC) has no effect on decreasing membrane fouling in both colloidal NOM removal and in alleviating membrane fouling generally [28,29]. Eventually, the pretreatment results

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*Corresponding author.

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in a partial removal of NOMs, such as dissolved organic carbon (DOC) with UV absorbance at 254 nm (UV_{254}). It has also been shown that the dominant membrane foulants have a very small fraction of NOM for non-absorbable UV light [30].

Studies on efficient NOM removal using a combination of pretreatments (adsorption) with low pressure driven membrane processes have received considerable attention in the last 10 years [31–33]. Three procedures have been studied for pretreatment that combine adsorption with low pressure driven membrane processes. For preadsorption filtration, feed water is first mixed with the adsorbent and then separated. Then, the preadsorbed feed water is filtered through the membrane. In direct filtration, feed water is filtered directly through the membrane after it is mixed with a suspended adsorbent. Although the first two of these combination processes provide some improvement in membrane performance, membrane fouling is still a major problem [14]. In predeposited dynamic membrane (DM) filtration, feed water is filtered through the membrane after the deposited adsorbent layer is formed on the membrane surface. In many studies, it has been observed that predeposited DM using heated aluminum oxide particles (HAOPs) or heated iron oxide particles (HIOPs) dramatically decreases NOM membrane fouling [31–34], the growth of a NOM fouling layer was hindered by HAOPs and HIOPs on the membrane surface conducting as a protective. This positively affects membrane flux recovery, product quality, and the operational cost of MF and UF membrane processes. Membrane systems can be cleaned with periodic backwashing of saturated adsorbent and reinjection of fresh adsorbent during filtration.

Although DMs with HAOPs enhance membrane filtration performance, predeposited DMs are complicated due to the membrane pore and particle sizes. In addition, these systems apply only to polymeric (Po) membranes. Ceramic (Ce) membranes are a new material having extremely high chemical and physical stability, outstanding separation characteristics, and a long operating life [35–37]. Moreover, compared to the Po membranes, Ce membranes have a lower degree of fouling and higher permeability [38,39].

For these reasons, we focused on the investigation of the interaction between NOM and two different types of membranes (Po and Ce MF), with respect to HAOPs. The NOM fraction change (i.e. amount remaining after HAOPs adsorption) was investigated. The fouling mechanisms were determined by investigating the non-adsorbed and adsorbed NOM in terms of MF permeability with different membrane types, with a broad adsorbent particle size range. In addition, the degree of membrane fouling was evaluated and compared using the resistance-in-series model.

2. Materials and methods

2.1. Feed water, adsorbents, and membrane

All experiment reagents for fouling and cleaning were obtained from Sigma-Aldrich (USA).Humic acid (HA) was dissolved in deionized (DI) water and pH was adjusted by 0.1 M NaOH and HCl. The concentration of DOC and UV_{254} were 1.152–1.244 mg L^{-1} and 0.078–0.092 cm^{-1}, respectively. The synthetic feed water was kept at 4°C in sterilized glass bottles. Two solutions (0.5 mM $NaHCO_3$ and 10.0 mM NaCl) were used to adjust the electro conductivity to 1,734 µS cm^{-1}.

HAOPs were used to determine the potential of NOM fouling reduction as a dynamic membrane material on Po and Ce membranes. Initially, 1.5 M of $Al_2(SO_4)_3{\cdot}18H_2O$ was neutralized to pH 7.0 with NaOH. Next, the resulting suspension was heated in a closed container to 110°C for 24 h. After cooling to room temperature, the suspension was repeatedly rinsed with DI water to remove dissolved salts.

Ce MF membrane discs with a nominal pore size of 0.2 µm were obtained from Sterlitech Corp. (Kent, WA, USA). The membrane was 2.5 mm thick and 47 mm in diameter with an effective surface area of 17.3 cm^2. These membranes have a strong resistance to pressure and temperature, up to 4 bars and 350°C, respectively. They have a pH range of 0–14. Flat type polyvinylidene fluoride (PVDF) MF membranes (Millipore, Bedford, MA, USA) with pore sizes of 0.22 µm and surface area of 55.4 cm^2 were used in most of the filtration experiments. The characteristics of the Ce and Po membranes are summarized in Table 1.

2.2. Adsorption experiments

The adsorption kinetic experiments were performed at pH 7.0. First, 0.1 g of adsorbent (HAOPs; Virgin, <75 µm, <150 µm) was mixed with 30 mL of HA stock solution in a polyethylene tube. This mixture was agitated using a rotary shaker at 200 rpm for 2 h. The sample tube was then filtered using a 0.45 µm cellulose fabric membrane prior to NOM analysis (UV_{254}, DOC). All adsorption experiments were carried out in duplicate. For adsorption isotherm experiments, 0–0.5 g of adsorbent was agitated with 30 mL of HA stock solution for 1 h at the initial pH of 7.0 using a rotary shaker. The experimental procedures for the adsorption isotherm experiments are the same as those described for the kinetic adsorption experiments.

2.3. Membrane filtration

The bare Ce and Po membranes were soaked with DI water for 2 h prior to filtration. DM was formed by pre-filtering 500 mL of DI water with HAOPs. Virgin and sieve adsorbents (<75 µm, <150 µm) at 0.05, 0.1 Al g cm^{-2} were applied to compare treatment efficiency by surface loading of the HAOPs. During the filtration, the adsorbent was predeposited on the membrane surface. Then, DI water was filtered to determine the stable operating flux. Transmembrane pressure (TMP) was maintained in dead end mode under a constant TMP of 50±0.5 kPa. Hydraulic backwash-

Table 1
The characteristics of the Ce and Po membrane

	Material	Pore size (µm)	Contact angle (°)	Active layer thickness (µm)
Ce	TiO_2 (surface) Al_2O_3, TiO_2, ZrO_2 (support)	0.2	15.6±3.4	27±1.7
Po	PVDF	0.22	69.3±2.9	100-125

ing was then performed for 2 min at a TMP of 80±0.5 kPa. The used Ce membranes were rinsed by soaking in NaOCl (3,000 mg/L) for 2 h. The Po membranes were rinsed in a 0.1 N NaOH solution at room temperature for 30 min. The DM formation and filtration experiments were carried out in duplicate.

2.4 Resistance-in-series model

In order to describe the overall characteristics of flux decline with a normalized form of the resistance-in-series model, the following equation was used during the filtration experiment:

$$J = \frac{\Delta p}{\mu R_t} = \frac{\Delta p}{\mu\left(R_m + R_{pr} + R_{cr} + R_{ir}\right)} \tag{1}$$

where J is the filtrate flux (m/s), Δp is the transmembrane pressure (kPa), μ is the solution viscosity (Pa, s), R_t is the total resistance (m^{-1}), R_m is the resistance of the clean membrane (m^{-1}), R_{pr} is the physical resistance (m^{-1}) removed by hydraulic backwashing, R_{cr} is the chemically reversible resistance (m^{-1}) removed by chemical cleaning, and R_{ir} is the chemically irreversible resistance (residual resistance after chemical cleaning, m^{-1}). Each resistance can be measured from the specific flux at the end of the filtration step.

2.5. Analysis

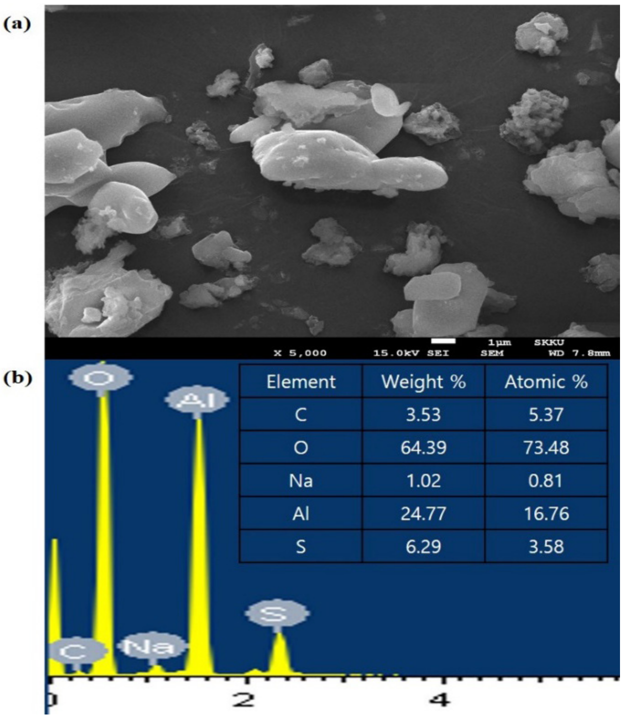
The morphology and surface element distribution of the HAOPs were analyzed using a scanning electronic microscope with an X-ray energy dispersive spectrometer (SEM-EDX, S-3400N, Hitachi, Japan). Concentrations of DOC and UV_{254} were determined using a total organic carbon (TOC) analyzer (TOC-VCPH, Shimadzu, Japan) and an ultraviolet-visible (UV-VIS) recording spectrometer (DR6000, HACH, USA), respectively. The fluorescence excitation-emission matrix (FEEM) spectra were investigated using a fluorescence spectrometer (FR-6000, SHIMADZU, JAPAN) at an excitation and emission wavelength range of 200–550 nm. All samples were filtered using 0.45 µm cellulose fabric membranes.

3. Results and discussion

3.1. Removal of NOM with HAOPs in adsorption

Fig. 1 shows an SEM image combined with EDX on the HAOPs surface. The HAOPs are aggregated with large and board-like shapes due to the many aggregates. The HAOP surfaces are occupied with 73.5% oxygen and 16.8% aluminum (Al), and a few salt elements. Al can involve a bridging cation as the binding humic substance. Carboxyl and hydroxyl functional groups are known to form very stable complexes with many metal cations or hydroxyl metal cations with $Fe^{3+} > Al^{3+} > Pb^{2+} > Ca^{2+} > Mn^{2+} > Mg^{2+}$ [40]. The surface adsorption of Al oxides using aluminol OH groups occurred by replacing the humic substance carboxyl groups from the solutions with hydroxide groups.

The simple adsorption of fulvic acids on aluminar is similar to that of humic substances. It is consistent with the ligand exchange mechanism. This means that the HAOPs exhibit positive effects in the adsorption of NOMs. XRD patterns of HAOPs have several peaks that exhibit a slightly crystalline structure (Fig. 2). Based on the peaks, the bayerite ($Al(OH)_3$) was indicated at diffraction angle (2θ) values of 33.5, 35.8, and 56.1 due to the enhanced hardness from the hydrothermal treatment [41].



Element	Weight %	Atomic %
C	3.53	5.37
O	64.39	73.48
Na	1.02	0.81
Al	24.77	16.76
S	6.29	3.58

Fig. 1. SEM image (a) and EDX surface analysis (b) of HAOPs.

Based on UV_{254}, the isotherm and kinetic adsorption of NOM from HA solution on HAOPs is presented in Fig. 3. Although UV spectroscopy is not significant for the direct determination of functional groups in these materials [42], it can provide some structural information about the NOM. As the wavelengths become shorter, the UV spectra (λ = 200–380 nm) of water and the DOC hydrophobic acid fraction show no increase in absorptivity. This is similar to humic substances in many environments [43]. As shown in Fig. 3a, the NOM adsorption increased gradually with increasing HAOPs doses, indicating a maximum of 90% NOM removal for virgin HAOPs (vHAOPs). When micro HAOPs (µHAOPs) were added, a maximum UV_{254} removal of ~86% and ~88% was observed. However, the removal did not remain constant for doses greater than 0.1 g. NOM has a combination of adsorbable and non-adsorbable fractions. Both fractions can be removed by HAOPs, such as when specific UV absorbance (SUVA) is less than 2 L mg m^{-1} with the non-adsorbable fraction coincident to this point on the ordinate as shown in Fig. 3a. The NOM adsorption immediately occurred on both HAOPs. More than 80% of the NOM was removed within 20 min. Adsorptivity was almost equilibrated after NOM removal, indicating either HAOPs microporosity or NOM molecule accessibility [43].

FEEM spectra consist of 5 regions and are diversely used to investigate organic components in surface water

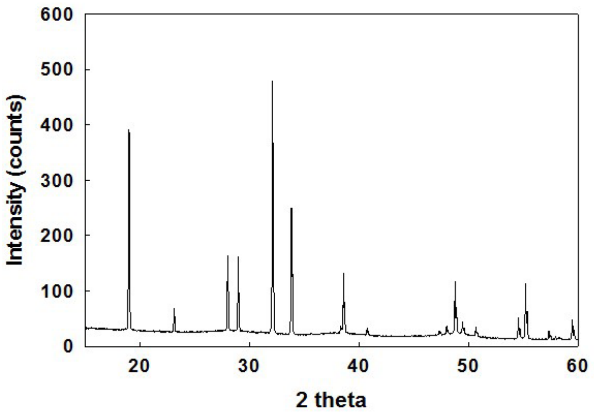


Fig. 2. X-ray diffraction patterns for HAOPs.

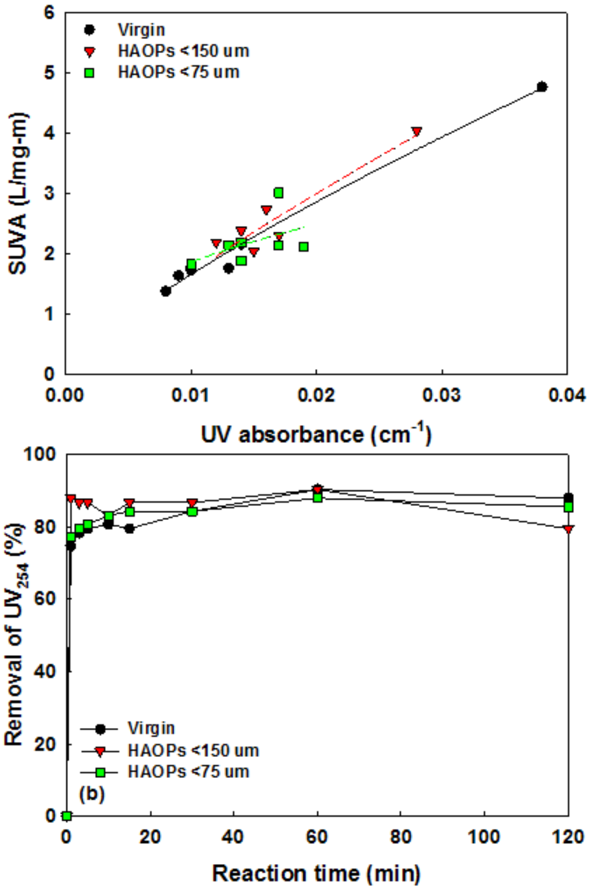


Fig. 3. NOM removal from HA solution by adsorption on HAOPs ((a) adsorption isotherm, (b) adsorption kinetics).

and treated wastewater [44]. Aromatic proteins occur in regions I (Ex/Em: 220–270 nm/280–330 nm) and II (Ex/Em: 220–270 nm/330–380 nm). Fulvicacid- (FA)-like substances occur in region III (Ex/Em: 220–270 nm/380–540 nm). Region IV(Ex/Em: 270–440 nm/280–380 nm) indicates soluble microbial products (SMPs, e.g. proteins and polysaccharide like materials) and Region V (Ex/Em: 270–440 nm/380–540 nm) indicates HA-like materials. The FEEM spectral features of NOM after kinetic (10 min) adsorption are shown in Fig. 4. The fluorophores decreased during adsorption on HAOPs. Reductions of conspicuous fluorescence intensities occurred in all regions except for region III. This is likely due to the changes of the NOM molecular distribution or chemical composition and indicates that aromatic proteins and polysaccharide-like and HA-like materials are removed almost instantly. However, the retained FA-like materials may perform important roles in membrane fouling. Based on this result, the adsorption capacity did not increase with smaller HAOPs size (Fig. 3b). Because virgin size particles aggregate with primary particles, primary particle surface area is significantly accessible to NOM after virgin size particle aggregation [43]. NOM adsorption capacity on µHAOPs was at a rate comparable to that on the vHAOPs. However, µHAOPs were adsorbed considerably faster during the first 20 min of contact. Therefore, the key to operating DM filtration effectively using HAOPs is to optimize adsorbent size.

3.2. *Polymeric and ceramic filtration with DM*

The permeability and fouling of DM filtration using vHAOPs on Po and Ce membranes are shown in Fig. 5. In a prior study, surface water was filtered through the DM containing micro size HAOPs. Fouling was reduced with increased surface loading of the HAOPs mass. This indicated that DM fouling was caused by foulant accumulation, where the foulant penetrated the DM, creating deposition on the membrane surface [45]. However, the same trend did not occur in this experiment when vHAOPs was loaded. The fouling on the Po membrane had a smaller effect than on the Ce membrane due to the formation of unstable DM with vHAOPs on the Po membrane. Despite NOM removal, the permeability was reduced immediately in both DM filtrations.

A combination of pore blocking and cake filtration models can be used for NOM fouling on the microfiltration membrane due to the physical deposition of large HA aggregates on the surface of the membrane [46,47]. Although the same trend occurred during each membrane filtration, the permeability of DM on the Ce membrane approached a steady state after 15 min, resulting in the predeposited form of the HAOPs. This caused HAOPs to be significantly stable on the Ce membrane and efficiently controls membrane fouling. In addition, HA filtration on the DM with vHAOPs shows that cake formation is negligible at short filtration times, but occurs during long filtration times [48]. This implies that vHAOPs have no significant effects on improving the permeability of both Po and Ce membranes.

When the HA solution was filtered through the DM with µHAOPs using both Po and Ce membranes, the fouling of the Ce membrane decreased and more stable permeability occurred compared to that in the DM with vHAOPs filtration (Fig. 6). In the earlier experiments using vHAOPs, HA solution was filtered through the Po and Ce membranes and the same trend was observed. The membrane fouling had penetrated the DM and deposited foulants on the membrane surface [41], but this did not occur when the Ce membrane was used. For example, in the µHAOPs filtration, permeability recovery was greater than 90% as HAOPs mass reduced from 0.1 to 0.05 Al g cm^{-2} and the particle size decreased (Figs. 5

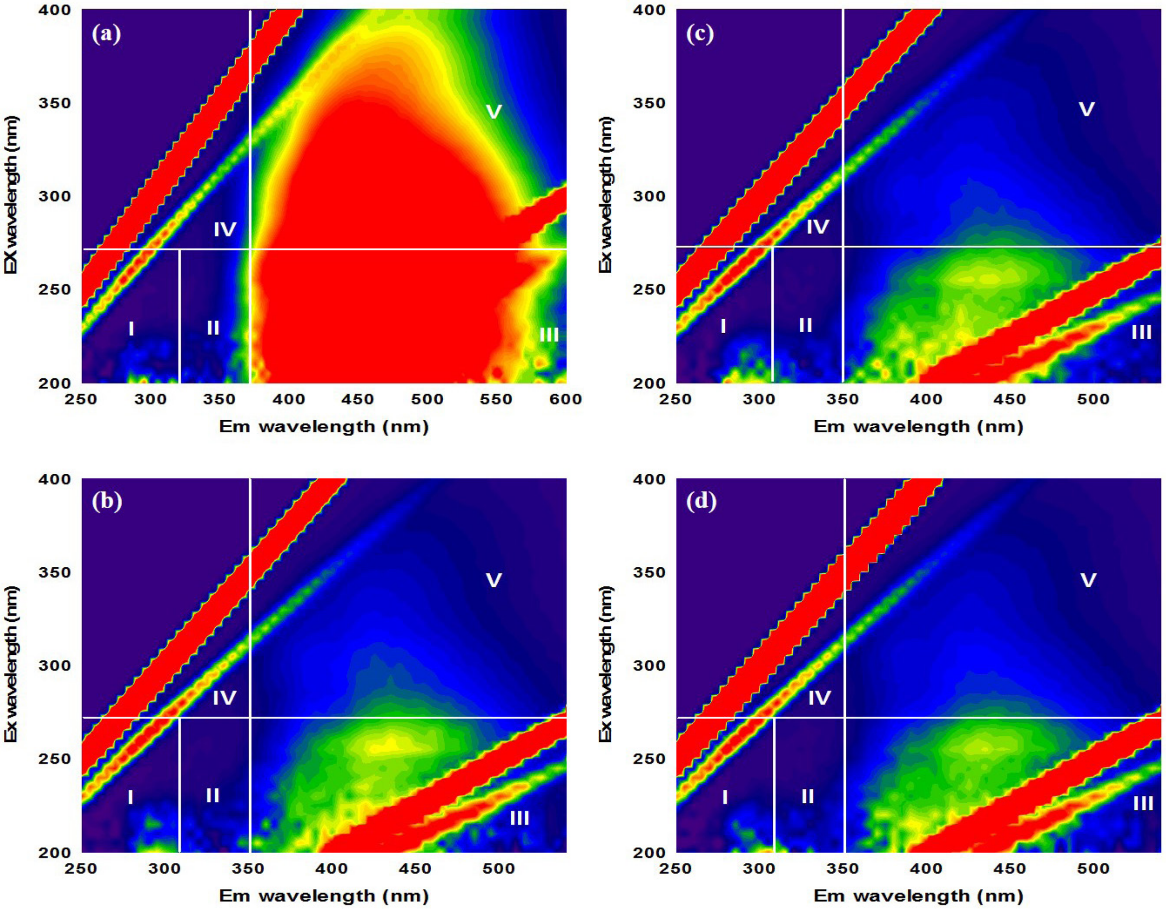


Fig. 4. Fluorescence EEM spectra of NOM after adsorption kinetic (10 min): HA (a), virgin (b), <150 μm (c), and <75 μm (d) HAOPs.

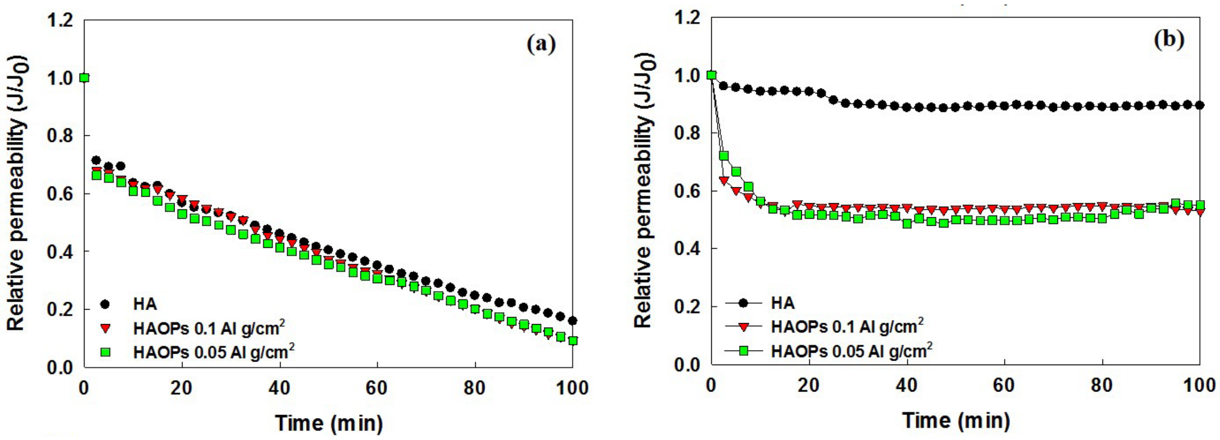


Fig. 5. Membrane fouling during DM filtration in the Po membrane (a) and Ce membrane (b) with varying surface loadings of vHAOP.

and 6). The fouling control decreased with increased vHAOPs surface loading as a result of membrane fouling from foulant accumulation caused by cake layer penetration. This was not dominant in DM filtration using the Ce membrane. Specifically, most of the foulant is on the surface or inside the DM, and the adsorbent layer itself then forms the fouling. The filtration portion of DM adsorbs foulants, which alleviates membrane fouling more efficiently with adsorbent sizes. As a result, increasing the DM thickness and adsorbent size causes insensitivity to the fouling reduction between the treatment portion of DM and the bare membrane. In the Ce membrane, adsorptive filtration with HAOPs is not dependent on surface loading, but on particle size. Further, it is more stable and efficient than DM filtration using the Po membrane.

The two DM fouling mechanisms on the Ce membrane are depicted in Fig. 7.When feed water containing a large amount of potential foulant is filtered through the DM by small size adsorbents, most of the large foulants such as colloids/particles and soluble NOM are captured on the DM surface and in the DM, fouling the membrane immediately. Small size adsorbents lead to more adsorptive and permeable DM formation and increase the mutual interactions between adsorbents and foulants. Fouling with smaller size adsorbents was formed primarily by the foulant accumulation on the membrane surface captured while passing through the DM. Fouling on the membrane can be removed easily by hydraulic backwashing, indicating reversible fouling. This mechanism corresponds to the experimental results of DM filtration by μHAOPs. On the other hand, in the presence of DM with large size adsorbents, permeability was significantly affected. However, increased NOM removal was observed. NOM fouling dominates in cases with large size adsorbents, smaller foulants, and small pores. This is because they move easily and are deposited inside DMs that have large size adsorbents. This can be the cause of irreversible adsorption on DM, including irreversible fouling on the membrane. Therefore, DM filtration using large size adsorbent changes the dominant fouling mechanism from reversible cake formation on the membrane surface to irreversible pore blocking. The two fouling mechanisms, membrane permeability and DM adsorptivity, depend on adsorbent size.

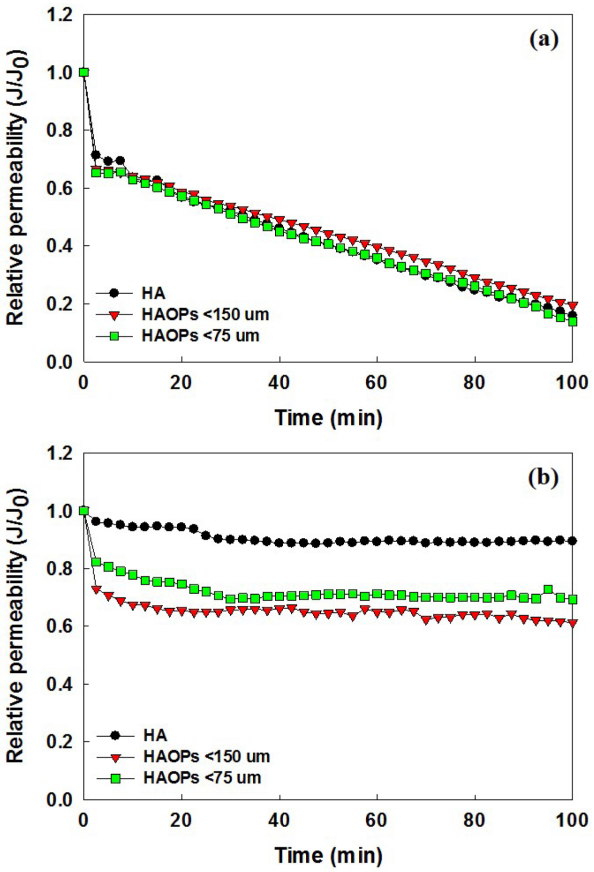


Fig. 6. Membrane fouling during DM filtration in the Po membrane (a) and Ce membrane (b) with varying size of HAOPs (<150 μm, <75 μm for 0.05 Al g/cm^2).

3.3. Water quality after DM filtration in both membranes

The results of water quality parameters (UV$_{254}$, DOC, and SUVA$_{254}$) after DM filtration are presented in Fig. 8. Substantial amounts of NOM were immediately removed by predeposited HAOPs on the membrane surface within 1 min and the removal efficiency of UV$_{254}$ was more than 80% in both membranes. NOM filtered through both DMs and formed a residue in the permeate at the beginning of the filtration. The end of the filtration was not terminated completely by predeposited HAOPs. This result corresponds to that in a previous study [31,32], where HAOPs more efficiently removed UV$_{254}$ than DOC due to binding selectivity to more hydrophobic molecules [49]. After DM filtration in the Po membrane (although permeability has no significant effect by HAOPs), the water quality parameters were bet-

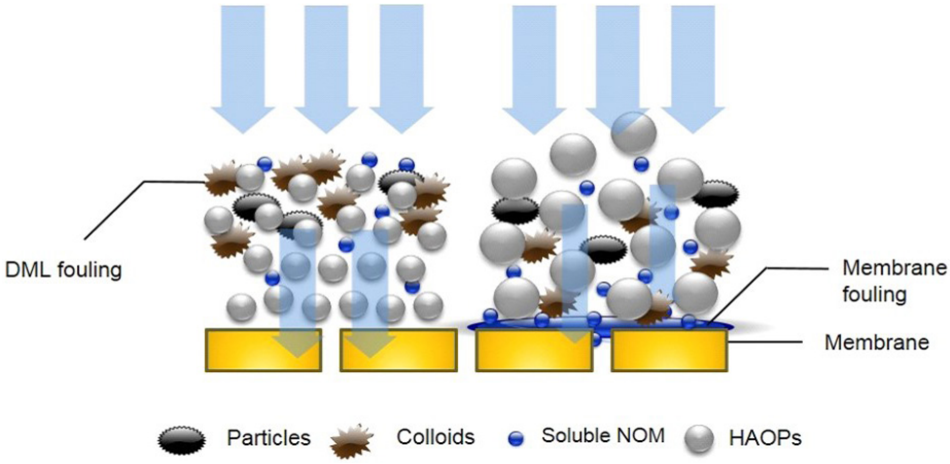


Fig. 7. Fouling mechanism of foulant-foulant and foulant-adsorbent interaction for vHAOPs (right side) and μHAOPs (left side).

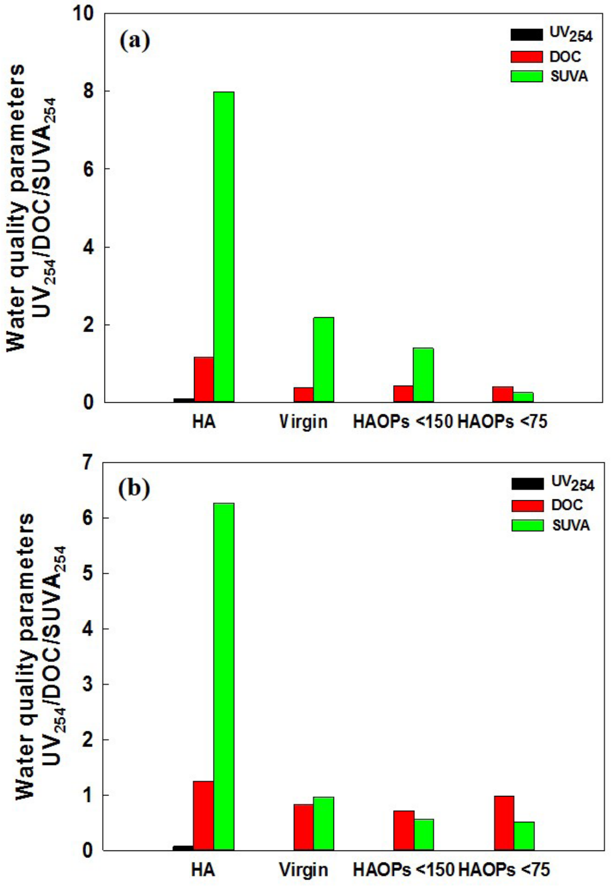


Fig. 8. The results of water quality parameters (UV_{254}, DOC, and $SUVA_{254}$) after DM filtration with Po (a) and Ce (b) membrane.

ter than the Ce membrane DM filtration, and the removal efficiency increased with decreasing HAOPs size. The surface area of the Po membrane was 55.4 cm^2 and was larger than that of the Ce membrane, indicating that substantially more NOM might contact the HAOPs. Therefore, more NOM can be removed with the Po membrane. When µHAOPs was predeposited on the Ce membrane, the maximum UV_{254} removal increased slightly compared to that in the Po membrane, and permeability increased steadily to 20% (Figs. 5b and 6b) compared to vHAOPs DM filtration. These results show that UV_{254} may not be suitable for indicating membrane foulants in NOM [43,50,51]. They also show that HAOPs selectively remove NOM from high molecular weight fractions [50] in the beginning of filtration. One possible inference is that more micropores were made accessible by the µHAOPs and membrane fouling was caused by a small hydrophilic fraction [45].

3.4. Resistance-in-model analysis

The results of resistance-in-series model analysis for the filtration of Po and Ce membranes with or without HAOPs are shown in Fig. 9. The intrinsic membrane resistance for R_m is negligible due to the micro pore sizes of either 0.2 µm or 0.22 µm [52]. The membrane resistance was higher for the ceramic membrane, which occurred in the relatively smaller contribution of initial pure water permeability, compared to that in Po membrane filtration. In all cases of Po membrane filtration, R_{ir} significantly contributed to the resistance, indicating that a large portion of membrane permeability cannot be recovered by simply hydraulic backwashing with permeate. When the NOM was filtered through to the Ce membrane with µHAOPs, R_{ir} did not significantly contribute to the Ce membrane. A distribution of resistance was used to determine the membrane fouling and the HAOPs characteristics on the Po and Ce membrane filtration. First, R_t has no significant effect on HAOPs using the Po membrane, while each resistance dramatically changed when using the Ce membrane. For the Po membrane, R_{ir} was not decreased by HAOPs, indicating unstable predeposited HAOPs, causing irreversible fouling. Second, R_{ir} with µHAOPs was negligible in the Ce membrane. After chemical cleaning, the initial pure water permeability was almost completely recovered. In contrast, significant irreversible fouling increased with decreasing HAOPs size on the Po membrane. This may induce detrimental fouling in long term operations. This means that it was possible to conduct harsher high frequency chemical cleaning for the Po membrane than for the Ce membrane. As described in section 3.3, the major contributor to NOM removal is the hydrophobic interaction between HAOPs and NOM [49]. The adsorption between organic materials and the Po membrane was stronger than in the Ce membrane due to hydrophobic interactions [47]. Therefore, in the Po membrane, the smaller HAOPs size would be det-

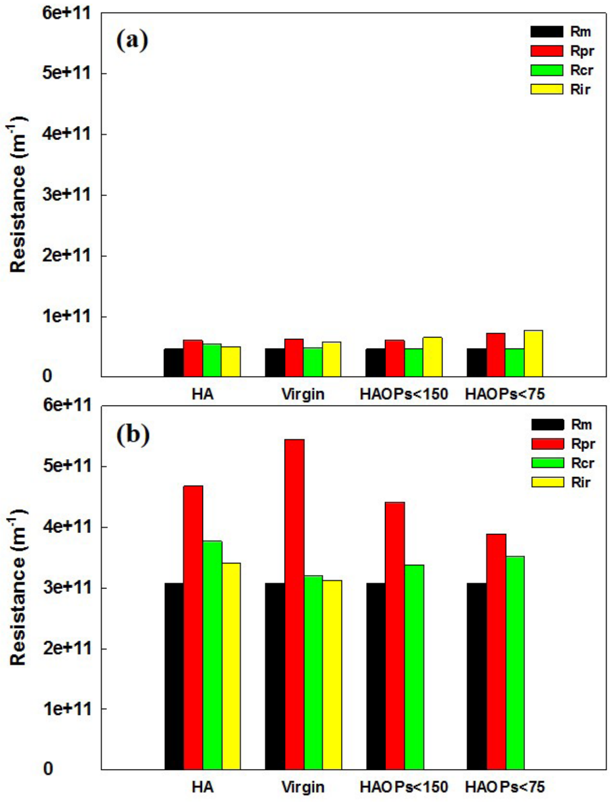


Fig. 9. Results of resistance-in-series model analysis for the filtration of Po (a) and Ce membrane (b).

rimental to membrane fouling, despite the high removal capacity for NOM.

All the resistance portions decreased dramatically as HAOPs size decreased in the Ce membrane (Fig. 9b). The smaller HAOPs predeposited, and the formed DM allowed greater adsorptivity and permeability of the Ce membrane. The physicochemical removal resistance (R_{pr} and R_{cr}) accounted for most of R_t for the Ce membrane with µHAOPs. However, R_{ir} contributed more to the Po membrane, indicating a more favorable interaction between HAOPs and Ce membrane surfaces. The definition of each resistance step may not directly relate to the fouling mechanisms in filtration models. For example, pore blocking in the fouling might cause removal of R_{pr} and R_{cr} by physicochemical washing. In filtration models, cake formation might cause severe membrane fouling that cannot be removed by physical hydraulic backwashing. In this experiment, after physicochemical washing, the Ce membrane permeability recovered to 90.3%, and then gradually increased to 100% due to predeposited µHAOPs. Only 95% could be recovered from the Po membrane, indicating the critical advantage of the Ce membrane with HAOPs. Overall, these results strongly suggest that the fouling mechanism of the DM on the Ce membrane is due to the presence of a stable cake layer of NOM with HAOPs. A DM with smaller HAOPs would be more effective for enhanced adsorptivity and permeability on the Ce membrane than on the Po membrane. This is a critical advantage and important information for Ce membrane operation.

4. Conclusions

DM with HAOPs has a significant effect on filtration using Po and Ce membranes. Its characteristics and dominant roles were investigated. The HAOPs adsorption results show that most of the NOM, comprised of soluble components, was removed by HAOPs. DOC was not easier to remove than UV_{254} due to the binding selectivity for hydrophobicity. HAOPs are an effective tool to remove the aromatic proteins, polysaccharide-like materials, and HA-like materials of the NOM. In filtration, NOM molecules separate and accumulate in the DM, causing membrane fouling on or in the membrane. The role of the DM determines the filtration conditions for permeability and the fouling rate. For example, a DM comprised of smaller adsorbent particles readily captures both colloidal particles and soluble foulants. The fouling caused on top of the DM will dominate the mechanism of the membrane itself. Under this condition, the DM on the Ce membrane strongly intercepts foulants. In contrast, in DM on the Po membrane (where the membrane fouling is caused by the adsorbents), the use of the smaller adsorbent particles irreversibly exacerbates fouling. The results of the DM filtration test on the Po and Ce membranes with various adsorbent sizes and surface loadings of HAOPs indicate that DM filtration with the Ce membrane has more potential as an operating system for alleviating membrane fouling than that with the Po membrane.

Acknowledgments

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