Determination of mass transport characteristics for natural organic matter (NOM) in ultrafiltration (UF) and nanofiltration (NF) membranes

S. Lee*, Y. Shim*, In S. Kim**, S.K. Yim*** and J. Cho†
* Department of Environmental Science and Engineering, Kwangju Institute of Science and Technology (K-JIST), Oryong-dong, Puk-gu, 500–712, Gwangju, Korea
** Division of Water Supply and Drinking Water Management, Ministry of Environment, Korea
*** Kolon Engineering & Construction Co., Ltd., Yongin, Korea
† Corresponding author. (E-mail: Choj@kjist.ac.kr)

Abstract This study is mainly concerned with establishing a reliable method of the quantitative analysis of natural organic matter (NOM) transport characteristics through ultrafiltration (UF) and nanofiltration (NF) membranes with molecular weight cutoffs of 8000 (GM) and 250 (ESNA), respectively. Filtrations were conducted with a cross-flow filtration unit and hydrodynamic operating conditions were controlled by a $J_0/k$ ratio (the ratio of initial permeate flux [$J_0$] to a back diffusional mass transfer coefficient [$k$]). A four-parameter (the apparent mass transfer coefficient [$k_a$], the solute concentration near the membrane surface [$C_m$], the solute permeability [$P_m$], and the reflection coefficient ($\sigma$)) model based on concentration polarization and irreversible thermodynamics was used to manipulate experimental results quantitatively. With the values of the determined parameters, the transport characteristics of NOM due to different solution chemistries such as pH and ionic strength through UF/NF membrane pores were investigated. This model was also used to demonstrate the effects of NOM structure (hydrophobic/transphilic/hydrophilic) on transport through the membranes, with XAD-8/4 resins fractionation and isolation procedures. Four parameters estimated through the model were revealed to be relevant to elucidate the behaviors of NOM in membranes and corresponding transport-related results were in good agreement with the theoretical descriptions related to the interactions between NOM molecules and membrane surface/pores.

Keywords Concentration polarization; four-parameter model; irreversible thermodynamics; $J_0/k$ ratio; NOM transport

Introduction

With increasing applications of UF and NF in drinking water treatment processes for disinfection by-products (DBPs) minimization through NOM removal, better understanding of NOM transport characteristics through membrane pores has become increasingly important. Various studies have been conducted to qualitatively investigate mechanisms involved in pressure-driven membrane processes for NOM removal, such as steric exclusion, electrostatic repulsion, and hydrophobic interaction (Childress and Elimelech, 1996; Braghetta and DiGiano, 1997; Cho et al., 1999, 2000). Many researches have also been conducted to quantitatively estimate transport characteristics of various solutes such as protein (Kedem and Katchalsky, 1958; Tandon et al., 1994), sucrose (Sitharamayya and Mishra, 1988), polyethylene glycol (Poddar et al., 1989), dextran (Mochizuki and Zydney, 1992), lysozyme (Rabiller-Baudry et al., 2000), and ions (Palmeri, 1999; Garba, 1999) through membrane pores. However, until recently, quantitative analyses for NOM transport through membrane pores, especially with tight UF and NF membranes, have not been rigorously investigated mainly due to heterogeneous characteristics of NOM and complex interactions between NOM and membrane. The main objective of this study is to establish a reliable method of quantitative analyses for NOM transport through UF and NF membranes.
with respect to (1) solution chemistries such as pH and ionic strength which affect both NOM characteristics and membrane properties as well as (2) different NOM structures which are hydrophobic, transphilic, and hydrophilic NOM (Thurman and Malcolm, 1981; Leenheer and Noyes, 1984; Aiken et al., 1992). Four parameters estimated by the model were used to quantitatively determine (1) a dominant transport mechanism (either convection or diffusion), (2) effects of pH and ionic strength on NOM-membrane interactions, and (3) transport characteristics of each NOM constituent and important affecting factors. The model validity is then discussed concerning experimentally obtained results.

**Theories**

In this study an analytical method for experimental data is developed based on concentration polarization and irreversible thermodynamics. Filtration experiments were conducted at various \( J_0/k \) ratios to obtain at least 4 transport data that can be used to estimate parameters of the applied model (liner and nonlinear estimations of four parameters).

**Hydrodynamic operating conditions (\( J_0/k \) ratio)**

A \( J_0/k \) ratio can be used to control hydrodynamic operating conditions. At the same \( J_0/k \) ratio, it is hypothesized that solute rejection and flux decline trends for a given solute-membrane pair are almost identical (Cho et al., 2000). \( J_0 \) (initial pure water permeation flux (Eq. (1))) and \( k \) (back-diffusional mass transfer coefficient (Eqs. (2) and (3))) can be calculated by the following equations (Mulder, 1996). In this study only thin-channel-type module was used.

\[
J_0 = \frac{Q_p}{A_m} \tag{1}
\]

\[
k = 1.62 \left( \frac{UD^2}{d_h L} \right)^{0.33} \quad \text{ (thin - channel - type module)}
\tag{2}
\]

\[
k = 1.62D \left( \frac{Re \cdot Sc \cdot d_h}{d_h} \right)^{0.33} \quad \text{ (tubular - type module)}
\tag{3}
\]

Here, \( Q_p \) and \( A_m \) are permeate flow rate (cm³/s) and membrane surface area (cm²), respectively. Eq. (2) and (3) are derived from the Sherwood number (\( Sh = kd_h/D \)) with consideration of module configuration (flow regime), where \( U \) is the average velocity of the feed fluid (cross flow velocity (cm/s)), \( D \) is the diffusion coefficient of the solute (cm²/s) estimated by the Stokes–Einstein relationship, \( d_h \) is the equivalent hydraulic diameter (cm), \( L \) is the channel (or tube) length (cm), \( Re \) is the Reynolds number (\( d_h U/\nu \)), and \( Sc \) is the Schmidt number (\( \nu/D \)) (\( \nu \) is the kinematic viscosity of water (cm²/s)).

**Concentration polarization (CP)**

The following Eq. (4) is transformed from the CP relationship in order to linearly estimate the apparent mass transfer coefficient \( (k_a) \) and corresponding solute concentrations near the membrane surface \( (C_m) \) at various hydrodynamic operating conditions.

\[
\ln(C_b - C_p) = -\frac{1}{k_a} \cdot J_v + \ln(C_m - C_p)
\tag{4}
\]

Here, \( J_v \), \( C_b \), and \( C_p \) represent solvent flux, feed side solute concentration, and permeate side solute concentration, respectively. These values can be determined experimentally for both UF and NF membranes. By plotting \( \ln(C_b - C_p) \) versus \( J_v \) values obtained experimentally, \( k_a \) and \( C_m \) can be linearly estimated from the slope and intercept of the
straight line, respectively. Because $C_m$ is dependent on applied hydrodynamic operating conditions, it exhibited different values at different $J_0/k$ ratios.

Irreversible thermodynamics

Solute flux can be expressed by Eq. (5) suggested by Kedem and Katchalsky (1958) based on irreversible thermodynamics considering membrane as a black-box since transport mechanisms are not clearly understood.

$$J_s = P_m (C_m - C_p) + J_v (1 - \sigma) \cdot C^*$$  (5)

Here, $J_s$, $P_m$, $\sigma$, and $C^*$ represent the solute flux, the solute permeability (the diffusive transport of solute through the membrane pores), the reflection coefficient (which is a measure of the selectivity of a membrane for a certain solute), and the logarithmic average concentration ($C^* = (C_m - C_p)/\ln(C_m/C_p)$), respectively. The values of $C_m$ and $J_v$ can be obtained from Eq. (4), and $J_s$ equals the product of $J_v$ and $C^*$. Using experimentally determined parameters at different $J_0/k$ ratios including $(C_m - C_p)$, $J_s$, $J_v$, and $C^*$, $P_m$ and $\sigma$ can then be determined by a nonlinear estimation with a three-dimensional plot of $J_s$ versus $J_v$ versus $C^*$.

CP modulus and Peclet number (Pe)

The ratio $C_m/C_b$ is called the CP modulus (Eq. (6)) (Mulder, 1996). Behaviors of solute accumulation near the membrane surface at an applied hydrodynamic operating condition (i.e., $J_0/k$ ratio) can be parameterized using the CP modulus. The ratio can be calculated with $C_m$ determined by Eq. (4) along with measured $C_b$. The Peclet number $(Pe)$ can be defined as the ratio of convectional solute transport to diffusional solute transport through membrane pores. Therefore, solute transport is dominated by diffusion for $Pe < 1$ and by convection for $Pe > 1$ (Wiesner et al., 1993; Tandon et al., 1994). Solute transport through the membrane pores can be calculated by Eq. (5), which can be divided into two parts: diffusional transport (the first part of the right-hand side of the equation) and convectional transport (the second part of the right-hand side of the equation). In this study $Pe$ is defined as shown in Eq. (7). Using these two parameters, CP modulus and $Pe$, the effects of solution chemistries and NOM characteristics on the convectional or diffusional transport of NOM through the tested UF and NF membrane pores were investigated.

$$CP \text{ modulus} = \frac{C_m}{C_b}$$  (6)

$$Pe = \frac{(1 - \sigma)J_v C^*}{P_m (C_m - C_p)}$$  (7)

Methods

Membrane properties and NOM characteristics

Molecular weight cutoff (MWCO) value (provided by manufacturers), zeta potential (measured in the laboratory using the electrophoretic method), pure water permeability (PWP) (experimentally determined), and contact angle (measured by a sessile drop method) of membranes used in this study are listed in Table 1. Four different waters containing different NOM constituents (raw, hydrophobic, transphilic, and hydrophilic NOM) were used as feed waters (see Table 2) to demonstrate the effects of NOM structure on transport characteristics. Three different types of feed waters with different solution chemistries (Type I: pH 7 and 0.1 mM NaCl, Type II: pH 10 and 0.1 mM NaCl, and Type
Experimental and analytic procedures

First, using a bench-scale membrane filtration apparatus, initial $J_0/k$ ratio tests were performed with a deionized (DI) water, prior to actual tests with feed waters containing NOM, and each membrane (either GM or ESNA). A particular $J_0/k$ ratio was adjusted by controlling $J_0$ (controllable with trans-membrane pressure valve) and $k$ (changeable by cross-flow velocity control). Based on these pre-determined $J_0/k$ ratios, NOM filtration tests were performed with a feed water and a membrane. All of the filtration experiments were conducted in the recycle mode, as shown in Figure 1.

Second, using the CP relationship along with pre-determined $J_v$, $C_b$, and $C_p$ values at different $J_0/k$ ratios, two characteristic parameters, $k_a$ and $C_m$, were estimated by the linear estimation as described previously (Eq. (4)) for each test. Finally, using Eq. (5) based on irreversible thermodynamics along with the experimentally determined values of $(C_m - C_p)$, $J_s$, $J_v$, and $C^*$ at different $J_0/k$ ratios, the other two characteristic parameters, $P_m$ and $\sigma$, were estimated by the nonlinear estimation as described previously for each test. For the nonlinear estimations of $P_m$ and $\sigma$ with Eq. (5), STATISTICA (99 Edition, StatSoft, Inc., USA) was used to determine $P_m$ and $\sigma$ by plotting $J_s$ as functions of $(C_m - C_p)$, $J_v$, and $C^*$.

More details or experimental and analytic procedures can be found in the previous article (Lee et al., 2001).

Results and discussions

Characteristics of NOM transport through the UF membrane

The effects of NOM structure (raw, hydrophobic, transphilic, and hydrophilic) and feed...
water chemistries (pH and ionic strength) on NOM transport behaviors through the UF membrane (MWCO = 8,000) pores were investigated. Characteristic parameters ($k_a$, $P_m$, and $\sigma$), the CP modulus, and the $Pe$ determined by the applied model for each case are compared with respect to applied hydrodynamic operating conditions ($J_0/k$ ratio).

**Effect of NOM structure.** There are two sets of estimations (linear and nonlinear) using Eqs. (5) and (6) for four different feed waters (see Table 2; in case of raw feed water, Type III was used as feed water.) with the same UF membrane (MWCO = 8,000). Procedures of linear estimations for the determination of $k_a$ and $C_m$ using Eq. (5) and nonlinear estimations for the determination of $P_m$ and $\sigma$ using Eq. (6), are shown in Figures 2 and 3, respectively. Estimated parameters including $k_a$, $P_m$, and $\sigma$ are summarized in Table 3. In case of CP modulus (calculated by Eq. (6)) and $Pe$ (calculated by Eq. (7)), both maximum (obtained at the highest $J_0/k$ ratio) and minimum (obtained at the lowest $J_0/k$ ratio) values also appear in Table 3. The CP modulus can reflect how much NOM accumulates in the concentration polarization layer. The $Pe$ can be used to confirm which transport mechanism of either convection or diffusion dominates at a given condition. Since NOM rejection or NOM
transport (solute flux) is affected with applied hydrodynamic operating conditions, these two parameters (CP modulus and $Pe$) are a function of $J_0/k$ ratio. All of the feed waters were adjusted to exhibit the same conditions in terms of pH and ionic strength, as shown in Table 2.

Throughout the results shown in Figures 2–3 and Table 3, raw and isolated NOM constituents exhibited somewhat different transport characteristics even through the same UF membrane under the same pH and ionic strength, and estimated parameters demonstrated the effects of NOM characteristics on transport behaviors of each NOM fraction through the UF membrane pores. In all cases, $Pe$ was higher than 1.0, which implied that NOM transport through the UF membrane pores was dominated by convectional transport mechanism (note that relative molecular weight of each NOM fraction (Table 2) is much lower than the MWCO value of the UF membrane, providing the decrease in NOM rejection as $J_0/k$ ratio increases). As shown in Table 3, the $Pe$ depends more on an applied hydrodynamic operating condition than on NOM structure. As $J_0/k$ ratio increased, for all cases, $Pe$ also increased. In case of reflection coefficient ($\sigma$), the selectivity of the UF membrane was the

![Figure 3](https://iwaponline.com/ws/article-pdf/2/2/151/408068/151.pdf)

**Figure 3** Determination of $P_m$ and $\sigma$. Using experimentally estimated parameters at different $J_0/k$ ratios including ($C_m - C_p$), $J_s$, and $C^*$, $P_m$ and $\sigma$ were estimated by a nonlinear regression method with a three dimensional plotting of $J_s$ (VAR1) versus $J_v$ (VAR2) versus $C^*$ (VAR3) (membrane: GM (UF), feed waters: (a) raw water, (b) hydrophobic NOM, (c) transphilic NOM, and (d) hydrophilic NOM)

**Table 3** Summary of estimated parameters (effects of NOM structure for the UF membrane)

<table>
<thead>
<tr>
<th>Type of NOM</th>
<th>$k_a$ (cm/sec)</th>
<th>$P_m$ (cm/sec)</th>
<th>$\sigma$</th>
<th>CP modulus (Eq. (6))</th>
<th>$Pe$ (Eq. (7))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw</td>
<td>$3.1 \times 10^{-3}$</td>
<td>$1.7 \times 10^{-4}$</td>
<td>0.31</td>
<td>1.1 (0.5) $-1.4$ (4.5)</td>
<td>2.2 (0.5) $-53.1$ (4.5)</td>
</tr>
<tr>
<td>Hydrophobic NOM</td>
<td>$4.1 \times 10^{-3}$</td>
<td>$1.6 \times 10^{-4}$</td>
<td>0.35</td>
<td>1.1 (0.8) $-1.8$ (8.1)</td>
<td>1.6 (0.8) $-128.8$ (8.1)</td>
</tr>
<tr>
<td>Transphilic NOM</td>
<td>$3.3 \times 10^{-3}$</td>
<td>$1.7 \times 10^{-4}$</td>
<td>0.29</td>
<td>1.2 (0.6) $-1.9$ (9.8)</td>
<td>1.7 (0.6) $-131.1$ (9.8)</td>
</tr>
<tr>
<td>Hydrophilic NOM</td>
<td>$2.3 \times 10^{-3}$</td>
<td>$2.3 \times 10^{-4}$</td>
<td>0.25</td>
<td>1.3 (0.8) $-1.7$ (6.6)</td>
<td>2.6 (0.8) $-109.3$ (6.6)</td>
</tr>
</tbody>
</table>

1. The numbers in parentheses are applied $J_0/k$ ratios
lowest for the hydrophilic NOM fraction due to its relatively small molecular size and low charge density compared to other fractions, which can be also explained in terms of $k_a$ and $P_m$. Electrostatic repulsion between the negative-charged UF membrane surface/pores (Table 1) and the membrane surface containing carboxylic and phenolic functional groups from hydrophobic and transphilic NOM constituents (Table 2) enhanced the back diffusional transport of NOM away from the membrane surface, which results in increased $k_a$. However, in case of hydrophilic NOM, the CP modulus is relatively higher than other NOM fractions due to virtually no electrostatic repulsion, resulting in higher $P_m$.

**Effect of pH and ionic strength.** To investigate the effects of feed water chemistries such as pH and ionic strength on NOM transport through the UF membrane pores, three types of different feed waters were tested (see Table 2) and the corresponding results (estimated parameters) are summarized in Table 4. Linear and nonlinear estimation procedures shown in Figure 2 and 3 were also applied here using the exactly same way described in the previous section (Effect of NOM structure).

As shown in Table 4, as pH increases or ionic strength decreases, electrostatic repulsion between NOM molecules and the membrane surface/pores increase, which results in increased $k_a$, decreased $P_m$, and increased $\sigma$. These results are in good agreement with the membrane’s double layer compaction theory and the change of NOM characteristics depending on water chemistries. In this study, pH was more influential than ionic strength in terms of $k_a$ and $P_m$ with respect to interaction between NOM and the UF membrane. However, in the case of the CP modulus and $Pe$, there is no significant difference resulted from the variation of pH and ionic strength. For all the cases, NOM transport through the UF membrane pores was dominated by convection ($Pe > 1$) and the CP modulus increased as applied $J_o/k$ ratio increased. These results are attributed to that concentration polarization and dominant transport mechanism (either convection or diffusion) were mainly affected by the applied hydrodynamic operating condition. However, more severe changes in pH and ionic strength may cause the distinct differences in the CP modulus and $Pe$.

**Characteristics of NOM transport through the NF membrane**
Effects of different NOM fractions (raw, hydrophobic, transphilic, and hydrophilic) and feed water chemistries (pH and ionic strength) on NOM transport behaviors through the NF membrane (MWCO = 250) pores were also investigated. Parameter estimations and experimental procedures are almost the same with the case of the UF membrane except that the range of the applied $J_o/k$ was relatively lower due to the small permeate flux (low $J_o$ value) of the NF membrane, as compared to the UF membrane. Estimated parameters for each case were represented in Tables 5 and 6.

**Effect of NOM structure.** Parameter estimation procedures are the exactly same as the case of the UF membrane. The most significant differences between the NF membrane and the

<table>
<thead>
<tr>
<th>Feed water</th>
<th>$k_a$ (cm/sec)</th>
<th>$P_m$ (cm/sec)</th>
<th>$\sigma$</th>
<th>CP modulus (Eq. (6))</th>
<th>CP modulus (Eq. (7))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>$3.6 \times 10^{-3}$</td>
<td>$1.5 \times 10^{-4}$</td>
<td>0.34</td>
<td>$1.1 (0.5) - 1.2 (4.5)$</td>
<td>$2.1 (0.5) - 45.3 (4.5)$</td>
</tr>
<tr>
<td>Type II</td>
<td>$5.1 \times 10^{-3}$</td>
<td>$0.2 \times 10^{-4}$</td>
<td>0.34</td>
<td>$1.0 (0.5) - 1.1 (4.5)$</td>
<td>$1.8 (0.5) - 33.4 (4.5)$</td>
</tr>
<tr>
<td>Type III</td>
<td>$3.1 \times 10^{-3}$</td>
<td>$1.7 \times 10^{-4}$</td>
<td>0.31</td>
<td>$1.1 (0.5) - 1.3 (4.5)$</td>
<td>$2.2 (0.5) - 53.1 (4.5)$</td>
</tr>
</tbody>
</table>
UF membrane are that (1) the $Pe$ is lower than 1.0 for all the cases, which means that NOM transport through the NF membrane was dominated by diffusion (for this case, NOM rejection increased as $J_0/k$ ratio increased) under the given hydrodynamic operating conditions, (2) the selectivity of the NF membrane for each NOM fraction was much higher than that of the UF membrane, and (3) somewhat different patterns of $P_m$ for the NF membrane were found compared to that of the UF membrane (much smaller NOM permeability for the NF membrane pores than the UF membrane pores). Similar to the results shown in Table 3, the hydrophobic NOM exhibited the highest $k_a$ and the hydrophilic NOM exhibited the highest $P_m$ value, resulting in the highest and lowest $\sigma$ values for the hydrophobic and hydrophilic NOM fractions, respectively. For all the cases, the CP modulus and $Pe$ increased as $J_0/k$ ratio increased, but slightly, as compared to the results of the UF membrane (Table 3).

Effect of pH and ionic strength. The effect of electrostatic interaction between NOM molecules and NF membrane was not significant compared to the UF membrane, even though there were slight differences in estimated parameters, which is due to the fact that the negative surface/pores charge of the NF membrane is much lower than that of the UF membrane (see Table 1). Thus, estimated parameters summarized in Table 6 did not exhibit big differences for all the cases. By comparing the results in Tables 5 and 6, it is found that structural difference in NOM was much more influential in transport behaviors through the NF membrane pores than pH and ionic strength (see the differences in $\sigma$, CP modulus, and $Pe$ for both the cases).

Conclusions
Throughout this study, NOM transport through both UF and NF membranes were quantitatively investigated using a transport model based on concentration polarization (Eq. (4)) and irreversible thermodynamics (Eq. (5)). Based on estimated parameters ($k_a$, $P_m$ and $\sigma$), the effects of NOM characteristics and solution chemistries on transport behaviors through both the membranes were successfully demonstrated. In the case of the UF membrane

### Table 5
Summary of estimated parameters (effects of NOM structure for the NF membrane)

<table>
<thead>
<tr>
<th>Type of NOM</th>
<th>$k_a$ (cm/sec)</th>
<th>$P_m$ (cm/sec)</th>
<th>$\sigma$</th>
<th>CP modulus (Eq. (6))</th>
<th>$Pe$ (Eq. (7))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw (unisolated)</td>
<td>$2.2 \times 10^{-3}$</td>
<td>$6.3 \times 10^{-6}$</td>
<td>0.77</td>
<td>1.0 (0.2) – 1.2 (2.3)</td>
<td>0.02 (0.2) – 0.11 (2.3)</td>
</tr>
<tr>
<td>Hydrophobic (XAD-8 isolated)</td>
<td>$1.2 \times 10^{-2}$</td>
<td>$4.4 \times 10^{-6}$</td>
<td>0.89</td>
<td>1.0 (0.4) – 1.1 (4.0)</td>
<td>0.02 (0.4) – 0.12 (4.0)</td>
</tr>
<tr>
<td>Transphilic (XAD-4 isolated)</td>
<td>$2.9 \times 10^{-3}$</td>
<td>$1.3 \times 10^{-6}$</td>
<td>0.82</td>
<td>1.0 (0.4) – 1.2 (5.1)</td>
<td>0.02 (0.4) – 0.11 (5.1)</td>
</tr>
<tr>
<td>Hydrophilic (XAD-8/4 passed)</td>
<td>$1.4 \times 10^{-3}$</td>
<td>$4.7 \times 10^{-5}$</td>
<td>0.71</td>
<td>1.0 (0.7) – 1.3 (3.0)</td>
<td>0.03 (0.7) – 0.09 (3.0)</td>
</tr>
</tbody>
</table>

### Table 6
Summary of estimated parameters (effects of pH and ionic strength for the NF membrane)

<table>
<thead>
<tr>
<th>Feed water</th>
<th>$k_a$ (cm/sec)</th>
<th>$P_m$ (cm/sec)</th>
<th>$\sigma$</th>
<th>CP modulus (Eq. (6))</th>
<th>$Pe$ (Eq. (7))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I (pH 7, 0.1mM NaCl)</td>
<td>$2.5 \times 10^{-3}$</td>
<td>$5.2 \times 10^{-6}$</td>
<td>0.77</td>
<td>1.0 (0.2) – 1.2 (2.3)</td>
<td>0.02 (0.2) – 0.05 (2.3)</td>
</tr>
<tr>
<td>Type II (pH 10, 0.1mM NaCl)</td>
<td>$2.9 \times 10^{-3}$</td>
<td>$4.2 \times 10^{-6}$</td>
<td>0.79</td>
<td>1.0 (0.2) – 1.1 (2.3)</td>
<td>0.03 (0.2) – 0.06 (2.3)</td>
</tr>
<tr>
<td>Type III (pH 7, 10mM NaCl)</td>
<td>$2.2 \times 10^{-3}$</td>
<td>$6.3 \times 10^{-6}$</td>
<td>0.77</td>
<td>1.0 (0.2) – 1.2 (2.3)</td>
<td>0.02 (0.2) – 0.05 (2.3)</td>
</tr>
</tbody>
</table>
tested in this study, the effects of pH and ionic strength are more influential compared to difference in NOM structure due to the highly negative-charged membrane surface, which can be easily influenced by the solution chemistries such as pH, ionic strength, and divalent cation. In addition, estimated Pe revealed that NOM transport through the UF membrane was dominated by convection (Pe > 1), providing decreased NOM rejection as J0/k ratio increases. In case of the NF membranes tested in this study, transport characteristics were more affected by difference in NOM structure than solution chemistries, and NOM fraction transport through the membrane pores was dominated by diffusion (Pe < 1), providing increased NOM rejection as J0/k ratio increases. However, with the difficulty for applying the precise hydrodynamic operating conditions to all of the experiments with different membranes, distinct differences in CP modulus (Eq. (6)) and Pe (Eq. (7)) corresponding to applied J0/k ratio could not be observed. More experiments (with a high-pressure-range-covered pumping system so that a complete range of J0/k ratio can be available for a given membrane) are suggested in order to estimate characteristic parameters more accurately.

Acknowledgements
This work was supported by the Korea Science and Engineering Foundation (KOSEF) through the Advanced Environmental Monitoring Research Center (ADEMRC) at Kwangju Institute of Science and Technology (K-JIST), and also supported by a grant (code 4–1–1) from the Sustainable Water Resources Center of the 21st Century Frontier Research Program.

References


