A feasibility study on UV pretreatment for microfiltration and reverse osmosis membrane processes in wastewater reclamation

Ho-Young Jeong, Yoon-Jin Kim, Ji-Hee Han, Dong-Ha Kim, Jinsik Sohn, Sangho Lee and Soonho Park

ABSTRACT

Wastewater reclamation is where wastewater from various sources is purified so the water can be used by human consumption. Among many treatment options, membranes have gained an important place in wastewater reclamation. It allows the production of high quality water from wastewater, with a small footprint and affordable energy consumption. Nevertheless, membrane fouling is regarded as a serious problem due to the high fouling potential of wastewater. In this study, we applied ultraviolet (UV) processes as a pretreatment for membrane systems that are used for wastewater reclamation. Low pressure UV (LUV) and pulsed UV (PUV) were used to decompose or alter the organics in the feed water of the membranes. Effluent organic matter was characterized by total organic carbon (TOC) and UV absorbance (UVA). Also the effect of UV pretreatment on membrane fouling was investigated for microfiltration (MF) and reverse osmosis (RO) processes. The pretreatment of membranes using LUV or PUV was effective to control fouling of hollow fiber MF membranes. This is probably because of the reduction and modification of organics after UV treatments. However, the effect of UV pretreatment on RO flux was less significant, which is attributed to low fouling prophecy after MF treatment.

Key words | microfiltration, pulsed UV, reverse osmosis, ultraviolet, wastewater reclamation

INTRODUCTION

The progress of industrialization and urbanization has rapidly increased water demand in recent years, although water is becoming scarce. In this context, development of alternative water resources is essential in order to overcome the water shortage (Shon et al. 2004). Among many alternative sources of water, wastewater reclamation has received special attention as a viable solution to secure a sustainable water supply. It has also become an increasingly strategic water management option for growing communities worldwide due to enforced effluent disposal constraints.

Prior to the beneficial use, wastewater should be treated using effective treatment technologies that guarantee protecting public health and the environment and industry demands. Among the most promising technologies to achieve these mentioned objectives, membrane technology has been applied worldwide. Recent advances in membrane technology for wastewater reclamation contributed to its increasing recognition as a reliable technology for cost effective production of high quality effluents (Jarusutthirak & Amy 2001; Melin et al. 2006). Depending on the pollutants in feed water, various kinds of membrane can be used, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). Recently, hybrid systems combining MF or UF with RO have been applied to produce high quality water for industrial and indirect potable uses. The advantages of using membrane systems for wastewater reclamation include: (1) high quality of product water; (2) small footprint; (3) reduced chemical use; (4) easy and low maintenance.
(4) reduced sludge production; and (5) automatic control of processes (Chapman et al. 2002; Kim et al. 2002).

However, there are also disadvantages in membrane systems, such as fouling and membrane replacement. Fouling encountered in reclamation of wastewater raises serious design and operational concern. High concentrations of suspended solids (SS), colloids and microorganisms in wastewater effluent after secondary treatment may cause rapid and irreversible fouling of MF, UF, and RO membranes (Fabris et al. 2007). Therefore, application of membrane technology for wastewater reclamation requires extensive pretreatment.

One of the possible options for the pretreatment of membrane is using a ultraviolet (UV) process because it allows the disinfection of microorganisms and oxidation of organic matter. UV disinfection has been widely used in water treatment and other related areas due to its high inactivation efficiency of pathogens (Glaze & Kang 1989). Unlike chlorination, it does not produce disinfection by-products such as trihalomethane (THM). UV can also remove organic micropollutants through direct photolysis or advanced oxidation with H2O2 (Linden et al. 2005). Accordingly, UV prior to membrane filtration can reduce fouling due to microorganisms and organic matter.

Various types of UV lamps including low pressure UV (LPUV), medium pressure UV (MPUV), and pulsed UV (PUV) lamps have been studied by many researchers (Campbell et al. 1995; Sharpless & Linden 2003). LPUV emits a single wavelength at 254 nm which is close to the maximum microbial action spectrum. MPUV emits a wide range of wavelengths including UV and visible light. Special LPUV emitting two wavelengths at 185 and 254 nm is applied to remove total organic carbon (TOC) for producing ultrapure water. PUV is similar to MPUV but its UV intensity is higher. In PUV, flash lamps operate in the pulsed mode with peak intensities much greater than those that occur with continuous sources of the same average power. The pulse duration is typically in the microsecond time scale, whereas the interval between pulses is in the order of milliseconds. Commonly used xenon flash lamps are polychromatic in nature, providing continuous spectra between the wavelengths of 185–1,000 nm (Liang et al. 2005).

In this study, we applied UV process as a pretreatment for membrane systems that are used for wastewater reclamation. LUV and PUV were used to decompose or alter the organics in the feed water of the membranes. The effect of UV pretreatment on membrane fouling was investigated in the hybrid system of MF and RO.

**EXPERIMENTAL METHOD**

Secondary effluent from a full-scale wastewater treatment plant in Korea was used as the feed water of MF membranes. The pH and SS ranged from 6.9 to 7.5 and from 2 to 5 mg L⁻¹, respectively. The conductivity and total dissolved solids were 0.41 mS cm⁻¹ and 409 mg L⁻¹, respectively. Moreover, the TOC and chemical oxygen demand for the wastewater were 5.9 and 21.6 mg L⁻¹, respectively. First, the wastewater was treated using MF membranes. Then, the permeate from the MF treatment was used for RO tests. LUV and PUV (Green EnTech, Korea) were applied prior to MF.

In this study, two UV systems (LUV and PUV) were considered as the pretreatment for MF–RO systems. The advantages and disadvantages of these UV systems are shown in Table 1. Three different systems were compared to investigate the effect of UV pretreatment on flux through MF and RO membranes as well as removal efficiencies of pollutants. In the first (Figure 1(a)), feed water was treated by MF prior to RO test. In the second and third (Figures 1(b) and (c)), LPUV and PUV were applied prior to MF, respectively.

**Table 1 | Comparison of low-pressure UV and pulsed UV (USEPA 2003)**

<table>
<thead>
<tr>
<th>Comparative advantages</th>
<th>Low-pressure UV</th>
<th>Pulsed UV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher germicidal efficiency; nearly all output at 254 nm</td>
<td>• Higher power output</td>
<td></td>
</tr>
<tr>
<td>Smaller power draw per lamp (less reduction in dose if lamp fails)</td>
<td>• Fewer lamps for a given application</td>
<td></td>
</tr>
<tr>
<td>Longer lamp life</td>
<td>• Smaller reactors</td>
<td></td>
</tr>
<tr>
<td>More lamps needed for a given application</td>
<td>• Smaller footprint</td>
<td></td>
</tr>
<tr>
<td>Larger footprint</td>
<td>Higher operation temperature can accelerate fouling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Shorter lamp life</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Lower electrical to germicidal UV conversion efficiency</td>
<td></td>
</tr>
</tbody>
</table>
LUV experiments were carried out using a laboratory scale system as shown in Figure 2(a). The volume of the reactor was 0.7 L and a UV lamp was surrounded by a quartz pipe. A water jacket was applied to control the temperature of the solution. A magnetic stirrer was used at 200 rpm to mix the solution during the reaction.

As shown in Figure 2(b), PUV experiments were performed using a system consisting of a power supply, a xenon (Xe) lamp, and a UV reactor. The lamp could generate high speed PUV light. The reactor volume was 30 L. A cooling device was installed at the bottom of the UV reactor.

The power supply, which can generate current up to 2,000 V or 20 Hz, was used to turn on the lamp. The operating conditions for the LUV and PUV are presented in Table 2.

Figure 2(c) shows the schematic diagram of a laboratory-scale submerged hollow fiber MF system. The system consists of a feed tank, a membrane module, a suction pump, a flow meter, a digital pressure meter, a data logger, and a computer. Changes in transmembrane pressure (TMP) were continuously monitored by the pressure meter and recorded in the computer. The flow rate was frequently checked to guarantee constant flux condition. Total recycle
operation was implemented, in which permeate was returned to the feed tank. Details of the operating conditions are listed in Table 2. A commercially available MF (Econity, Korea) membrane was used for the tests. The membrane was made of polyethylene (PE) and its nominal pore size was 0.4 μm.

The RO tests were carried out using a stirred cell (Sterlitech HP4750, USA). A commercial RO membrane (Hydranautics, USA) was used. Batch reactors for LUV and PUV were used to apply UV to the wastewater. In some LUV tests, hydrogen peroxide (H2O2) was also used to create a stronger oxidation condition. The operating conditions for the RO and LUV/PUV are presented in Tables 3 and 4, respectively.

RESULTS AND DISCUSSION

Fouling of MF membrane by wastewater without pretreatment

Prior to UV pretreatment, the secondary sewage effluent was directly used as a feed solution for the submerged MF membrane, as illustrated in Figure 3. The experiment was carried out at constant flux condition (Jw = 50 L m⁻² hr⁻¹). Initially, the TMP was low (less than 0.07 bar) but increased with time. After 8 hr of operation, the final TMP was 0.41 bar, which corresponds to over six times larger than the initial TMP. Using the TMP data, the fouling resistance was analyzed based on the resistance-in-series model:

$$J_w = \frac{\Delta P}{\eta (R_m + R_c)}$$

where Jw is the water flux, ΔP is the transmembrane pressure, η is the viscosity of water, Rm is the intrinsic membrane resistance, and Rc is the fouling resistance due to deposition of particulate and organic matters. As also shown in Figure 3, Rc increases with time, indicating the secondary sewage effluent has high potential of MF membrane fouling. The Rm was only 4.0 × 10⁹ m⁻¹ but the Rc after 8 hr was over 2.9 × 10¹⁰ m⁻¹.

Table 2 | Operating conditions of laboratory-scale UV process test unit

<table>
<thead>
<tr>
<th>Item</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>V max</td>
<td>2,000 V</td>
</tr>
<tr>
<td>Pulse width</td>
<td>250 μs, Frequency: 20 Hz</td>
</tr>
<tr>
<td>P avg. max</td>
<td>4,577 W</td>
</tr>
<tr>
<td>P peak max</td>
<td>3,000 kW</td>
</tr>
<tr>
<td>Reaction time</td>
<td>2 min</td>
</tr>
</tbody>
</table>

Table 4 | Operating conditions of laboratory-scale RO process test unit

<table>
<thead>
<tr>
<th>Item</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane module</td>
<td>Stirred cell</td>
</tr>
<tr>
<td>Effective membrane area</td>
<td>3.14 cm²</td>
</tr>
<tr>
<td>Pressure</td>
<td>10 bar</td>
</tr>
<tr>
<td>Temperature</td>
<td>20 ± 5 °C</td>
</tr>
<tr>
<td>Solution</td>
<td>[Raw water, LUV, LUV + H2O2, PUV] + MF</td>
</tr>
</tbody>
</table>

Figure 3 | Dependence of flux and fouling resistance on time in MF treatment of the wastewater without pretreatment.
Since total recycle operation was applied, the concentration of foulants in the reactor \((C_f)\) is described by:

\[
V \frac{dC_f}{dt} = -J_w C_f A
\]

where \(V\) is the reactor volume, \(t\) is the time, and \(A\) is the membrane area. The \(R_m\) may also be given as a function of \(C_f\):

\[
R_m = \frac{\alpha V (C_{f,0} - C_f)}{C_f/C_0}
\]

where \(\alpha\) is the reactor volume and \(C_{f,0}\) is the initial foulant concentration in the feed solution.

Rearranging Equations (2) and (3), the following equation is derived:

\[
R_m = \frac{\alpha C_{f,0} V (1 - e^{-\frac{J_w A t}{C_0}})}{A}
\]

Here, \(\alpha C_{f,0}\) is the characteristic value to quantify the fouling potential of a feed water. Figure 4 illustrates the plot of \(R_m\) based on Equation (4). From the graph, the \(\alpha C_{f,0}\) for the wastewater was estimated to be \(2.2 \times 10^{11}\) m\(^{-2}\).

**Effect of UV pretreatment on fouling of MF membrane**

To mitigate MF fouling by the foulants in the wastewater, various UV techniques were applied as presented in Table 3. The doses of UV were set to very high values to maximize the anti-fouling effect. The results are shown in Figure 5. Compared with the case for the wastewater without UV pretreatment, fouling was less severe using the LUV pretreated wastewater. After 8 hr, the TMP for the LUV-pretreated wastewater was only 0.2 bar, which corresponds to 50% of the TMP for the original wastewater. It is evident from the result that the LUV pretreatment is effective to control fouling.

In general, pretreatment using LUV alone is not effective to control membrane fouling under mild irradiation conditions. In this study, however, UV dose was much higher \((1,110 \text{ mJ cm}^{-2})\) than the normal conditions for disinfection, which may lead to direct oxidation of organics.

As also shown in Figure 5, the use of \(\text{H}_2\text{O}_2\) with LUV did not result in an additional benefit. Considering the conditions, hydroxyl radicals could be formed to induce stronger oxidation reactions. Nevertheless, the TMP for LUV-pretreated wastewater in the presence of \(\text{H}_2\text{O}_2\) was almost identical to that without \(\text{H}_2\text{O}_2\). This may suggest that hydroxyl radicals do not play an important role in controlling fouling. On the contrary, PUV was the most effective to retard MF fouling. More than 60% of reduction in TMP was observed after 9 hr of filtration. This is also attributed to high dose of UV by high energy pulse lights.

Figure 6 shows the linear regression of experimental results with UV pretreatment based on Equation (4). From the slopes of the plots, \(\alpha C_{f,0}\) values for LUV pretreated wastewater, LUV/\(\text{H}_2\text{O}_2\) pretreated wastewater, and PUV pretreated wastewater were \(1.07 \times 10^{11}\), \(9.889 \times 10^{11}\), and...
7.54 \times 10^{10} \text{ m}^{-2}, \text{ respectively. These correspond to 79, 73, and 56\% of the } \alpha C_{f,0} \text{ value for wastewater without pretreatment, respectively. Either the initial concentration of foulant } (C_{f,0}) \text{ or foulant characteristics } (\alpha) \text{ may be changed.}

**Effect of UV pretreatment on water quality parameters**

Figure 7 compares TOC for wastewaters without and with pretreatments. Except for P6, which is the case for LUV and MF, the wastewater without UV pretreatments resulted in slightly higher TOC value than those with UV pretreatments. This is attributed to organic decomposition of UV with high dose. PUV was the most effective in reducing TOC (P3 and P4). Nevertheless, the application of MF after UV does not seem to effectively reduce TOC. This suggests that these organics are not retained by the MF membrane.

The UV absorbance values at 210 nm (UVA_{210}) for wastewaters without and with pretreatments are shown in Figure 8. UVA_{210} is reported to be proportional to the content of hydrophobic organics. Unlike TOC, the UVA_{210} is reduced after MF, indicating the hydrophobic organics are retained by MF membrane and may cause fouling. The UVA_{210} also decreases by UV pretreatment. Again, PUV was the most effective to reduce UVA_{210}.

It is likely that there is a correlation between the fouling rates and TOC/ UVA_{210} results. For instance, PUV reduces the TOC and UV in the feed water, leading to a reduction in fouling. Nevertheless, they did not quantitatively match. The fouling potential \alpha C_{f,0} decreased by 44\% after PUV pretreatment but UVA_{210} reduction was less than 5\%. In
summary, UV pretreatment is effective to control fouling not because it reduces the quantity of the foulants but affects the characteristics of foulants.

Effect of UV pretreatment on fouling of RO membrane

After MF experiments, the effect of UV pretreatment on RO fouling was also investigated in Figure 9. Nevertheless, it appears that the RO fouling rate is very low for all cases. This is because the feed water was already filtered by MF membrane, allowing the low fouling prophecy. A set of long-term experiments should be carried out to examine the UV pretreatment efficiency in RO systems.

CONCLUSIONS

The following conclusions can be drawn from this work. UV pretreatment of wastewater (secondary effluent) was effective to mitigate fouling of submerged MF membranes. The fouling potential $\alpha_{C_{f0}}$ was effectively reduced, indicating either the quantity or characteristics of foulants were changed.

After UV pretreatment, TOC and UVA$_{210}$ were reduced. Nevertheless, the amount of organic reduction by UV could not account for the anti-fouling effect. It was hypothesized that the UV altered the characteristics of foulant ($\alpha$), leading to fouling mitigation.

A high dose of UV seems to be required to obtain the pretreatment effect. Under these conditions, an addition of H$_2$O$_2$ was not effective. On the other hand, pretreatment using PUV was the most effective.

The effect of UV pretreatment on RO fouling in MF–RO hybrid system could not be investigated due to very low fouling prophecy. Clearly, a long-term study should be attempted to address this issue.

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