Desalination 398 (2016) 22–29

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Simultaneous dechlorination and disinfection using vacuum UV irradiation for SWRO process

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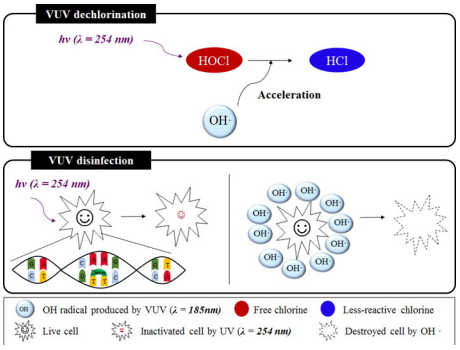
HIGHLIGHTS

- A VUV lamp was applied to achieve dechlorination and disinfection in SWRO process.
- The VUV lamp was energy-efficient to dechlorinate chlorine-added seawater.
- Low chlorine content (<0.07 mg/L) was achieved with stable flux and salt rejection.
- Additional disinfection effects of VUV irradiation reduced bacterial diversity.
- *Alcanivorax* sp. was suggested as a representative UV-resistant biofilm bacterium.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 5 April 2016
Received in revised form 27 June 2016
Accepted 11 July 2016
Available online xxxx

Keywords:
Dechlorination
UV irradiation
Vacuum UV lamp
Biofilm community
Seawater reverse osmosis process

ABSTRACT

The dechlorination effectiveness of ultraviolet (UV) irradiation and its effects on marine biofilm community were investigated in a pilot-scale seawater reverse osmosis (SWRO) process. Lab-scale feasibility tests were conducted for three sources of low-pressure UV (LPUV), vacuum UV (VUV) and medium-pressure UV (MPUV) lamps. As a result, a VUV lamp was chosen for the pilot process because this lamp ensured efficient dechlorination in raw seawater at UV dose < 700 mJ/cm^2. In a pilot plant test, the VUV irradiation successfully dechlorinated the seawater without damaging the reverse osmosis membrane. The VUV irradiation decreased the bacterial diversity of biofilm community. The results indicate that simultaneous dechlorination and disinfection were successfully achieved using VUV irradiation for SWRO. Therefore, the VUV irradiation can be used as an alternative dechlorination strategy in SWRO. This paper also provides the niche information of the UV-resistant microbial community; this information may be useful to guide the disinfection strategy further.

1. Introduction

The seawater desalination is an alternative way to overcome the world shortage of clean water. Reverse osmosis (RO) process is widely used for seawater desalination because it is inexpensive and scalable over thermal distillation processes such as multi-stage flash distillation (MSF) and multiple-effect distillation (MED) [1]. However, during seawater reverse osmosis (SWRO), an RO membrane often accumulates bacterial films that can reduce flow of water through it [2]; as a result, freshwater production decreases and the energy cost increases [3]. For this reason, various physico-chemical pretreatment techniques have been used to reduce this biofouling.

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http://dx.doi.org/10.1016/j.desal.2016.07.012
0011-9164/

Chlorination of the seawater is the most frequently used pretreatment technology to control biofouling in SWRO [4]. However, the injected free chlorine must be removed before the RO process because the amide functional bond of the RO membrane can be chemically broken by the oxidation potential of free chlorine [5]. In SWRO process, chemical treatment using sodium bisulfite (SBS; $NaHSO_3$) has been mainly used for dechlorination: in general, three times more SBS than residual free chlorine is applied to achieve efficient dechlorination [6]. However, SBS dechlorination can promote bacterial growth, which aggravates biofouling during SWRO [2,7]. Therefore, an alternative dechlorination process should be developed to suppress bacterial growth and ensure stable dechlorination.

Ultraviolet (UV) irradiation is an effective non-chemical dechlorination technology [8]. UV rays photolyze water to hydroxyl radicals (•OH), and free chlorine to chlorine radicals (Cl•) that convert free chlorine to less-reactive chlorides such as hydrochloric acid (HCl) [9]. UV irradiation can be a more-suitable dechlorination strategy for SWRO process than SBS dechlorination for following reasons. First, UV dechlorination can reduce the free chlorine without requiring additional chemicals, which enable to prevent the secondary pollution [8]. Second, the process operation and maintenance are relatively simple [8]. Third, UV rays can enhance water quality by degrading dissolved organic matters included in seawater [10]. Lastly, UV irradiation for dechlorination may cause multiple reactions that contribute to inactivation of the biofilm community [5]. In principle, UV irradiation inhibits the microbial activity by denaturing bacterial DNA [5]. The radicals produced by UV ray can also suppress microbial activity by providing oxidative stress [11]. However, UV irradiation also has disadvantages because it is expensive [12,13]. Nevertheless, UV irradiation can achieve both dechlorination and disinfection, so it can be considered as an option for dechlorination in SWRO. However, the application of UV for dechlorination in SWRO process remains limited.

Various UV sources can be used for dechlorination in SWRO. UV lamps are classified as low-pressure (LPUV), medium-pressure (MPUV) and high-pressure UV (HPUV) lamps according to the internal mercury gas pressure of the lamp. The LPUV and MPUV lamps have been mainly used for water treatment [14–16]. The LPUV lamp emits single wavelength of $\lambda = 254$ nm whereas the MPUV lamp emits multiple various wavelength of $200 \le \lambda \le 400$ nm [17]. The LPUV lamp can be modified by lamp-coating methods to produce either short monochromatic wavelength of $\lambda = 185$ nm or dichromatic wavelengths of $\lambda = 185$ nm and $\lambda = 254$ nm, i.e., a vacuum UV (VUV) lamp [11]. Recently, VUV lamps have also been used for water treatment, because it can emit a short wavelength of $\lambda = 185$ nm using same energy that an LPUV lamp uses. The $\lambda = 185$ nm of UV ray generates •OH that is strong reactive oxidant more efficiently than do longer-wavelength UV rays [11].

The knowledge of bacteria that form biofilms during SWRO would improve characterization of biofilm formation and guide optimization of process operation [5,18–20]. UV irradiation can be acted as the selection factor on biofilm-forming bacteria during SWRO. As mentioned previously, during UV dechlorination, biofilm-forming bacteria are exposed to a variety of microbial inhibitors, including free chlorine, UV rays, and radicals such as •OH or Cl•. However, the effects of UV dechlorination on the biofilm community in SWRO remain unclear. Therefore, niche differentiation caused by UV dechlorination should be investigated because microorganisms are subjected to the combined stresses of chlorine and UV irradiation.

This study investigated the efficacy of dechlorination by VUV irradiation in a pilot-scale SWRO process. First, a proper UV lamp was chosen after lab-scale comparisons of the effectiveness of LPUV, VUV, and MPUV lamps. This study identified VUV as the preferable process. Then pilot-scale VUV and SBS dechlorination processes were operated in parallel to compare their efficiency. Two pilot RO membrane processes, one combined with each dechlorination process, were operated to evaluate the effects of dechlorination strategy on water flux and salt rejection. Concurrently, marine biofilm community diversities and structures in the SWRO processes were investigated using taxonomic analysis based on 16S rRNA genes, and thereby provide information on the marine biofilm community structure after VUV irradiation.

2. Materials and methods

2.1. Lab-scale feasibility test

2.1.1. UV lamp and UV exposure apparatus

In a lab-scale feasibility experiment, the effects of various UV sources on the dechlorination efficiency were evaluated to guide selection of the appropriate UV source for the pilot plant. A10-W LPUV lamp, a 10-W VUV lamp and a 1.2-kW MPUV lamp were used in the tests. The LPUV lamp emits $\lambda = 254$ nm, the VUV lamp emits $\lambda = 185$ nm and $\lambda = 254$ nm, and the MPUV lamp emits various $200 \le \lambda \le 400$ nm. The UV exposure apparatus used for the feasibility test was prepared as described previously [9].

2.1.2. UV irradiation and dechlorination rate constant (k)

The lab-scale UV dechlorination tests were conducted in batch mode. A 100-mL sample was poured into a 250-mL beaker; it was placed on the stir plate and exposed to LPUV, VUV, or MPUV. A UV radiometer was used to measure the UV intensity [mW/cm^2] at the center of the UV beam on the stir plate; UV dose [mJ/cm^2] was calculated by multiplying UV intensity by exposure time [s] [9,21]. To monitor the dechlorination pattern, the residual chlorine concentration was measured during the UV irradiation. The concentration of the free chlorine was measured by using a chlorine (free and total) colorimeter II test kit (Hach, USA) that can detect $0.02 \le$ [free chlorine] ≤ 2.00 mg/L.

The tested free chlorine concentration was set to 1 mg/L by adding an appropriate amount of 4% NaOCl solution (Sigma, Aldrich); this free chlorine concentration is frequently used level in seawater desalination [22]. The residual chlorine was measured during UV irradiation, then the dechlorination rate constant k was calculated using a pseudo-first-order equation [9,23,24]:

$$-\ln \frac{[C]_F}{[C]_0} = kF \tag{1}$$

where $[C]_0$ is the initial free chlorine concentration and $[C]_F$ is the measured free chlorine concentration after exposure to the UV fluence F (mJ/cm^2); k (cm^2/mJ) is the fluence-based first-order rate constant.

First, as a control experimental trial, the dechlorination test was conducted in deionized (DI) water without any interfering chemicals or components. These experiments were performed at pH 5, 7 and 9. The dechlorination tests were conducted in two salt solutions: 1) a 3.5% (w/v) solution of commercial sea salt (Sigma, Aldrich), and 2) raw seawater (Table 1) obtained from Changwon, Korea.

2.2. Operation of pilot-scale dechlorination processes

The effluent of a sand filtration process was used as feed water. The residual chlorine concentration in the feed water was adjusted to 0.1–0.5 mg/L using 10% NaOCl solution. This chlorine-treated water was injected into pilot-scale dechlorination plants (Changwon, Korea), and

Table 1
Characteristics of seawater from Changwon City, Korea [1].

Component	Values
pH	8.3
TDS (mg/L)[a]	34,360
TSS (mg/L)[b]	13.8
DOC (mg/L)[c]	2.2
Total hardness (mg/L as $CaCO_3$)	6,217

[a] Total dissolved solid.
[b] Total suspended solid.
[c] Dissolved organic carbon.