ULTRAVIOLET TECHNOLOGY IN WATER RECLAMATION FROM SECONDARY EFFLUENT: A PERSPECTIVE FROM THE TROPICAL ENVIRONMENT

RONGJING XIE

Centre for Advanced Water Technology, Innovation Centre (NTU) Block 2, Unit 241
18 Nanyang Drive, Singapore 637723; E-mail: rjxie@cawt.sui.com.sg

ABSTRACT

Singapore's water reclamation process (known as NEWater production) consists of microfiltration, reverse osmosis and ultraviolet irradiation. In this process, UV unit operation is incorporated after the reverse osmosis membrane unit operation as an added safety barrier. Pilot and demonstration scale studies were conducted before full scale plants were built with comparable main unit operations. The existing three NEWater plants, capable of producing 96,000 m^3 per day of high quality water, employ either medium or low pressure UV systems. The fluence (UV dose) up to 90 mJ cm^{-2} (900 J $m^{-2)}$ ensures the efficacies for virus and pathogenic bacteria removal greater than 4 logs. NEWater meets all criteria of the WHO and USEPA drinking water standards and is primarily for use in electronic and semi-conductor industries. The success in NEWater production is opening a new approach of coping with the rising water demand.

Keywords: secondary effluent; microfiltration, reverse osmosis, ultraviolet disinfection, wastewater treatment

Note: The opinions presented in the paper are those of the author, not of his employer.

INTRODUCTION

With approximately 4 million population and well developed industries, Singapore consumes 1.4 million m^3 of water per day. Of this amount, the industries use roughly 50% of the total volume. The Public Utilities Board's Jorhor River Waterworks buys raw water from Jorhor State, Malaysia to meet half of the water demand. The raw water is treated and conveyed to Singapore via pipe lines. The five waterworks in Singapore produce potable water with feed from 17 reservoirs to supply the other half.

Singapore has two agreements with Malaysia: the 1961 agreement which expires in 2011, and the 1962 agreement which expires in 2061. The water issue has always been Singapore's vulnerability, dictated by the state of relationship between the two countries. This stimulates the national effort to achieve an ultimate self-sufficient water supply, including better catchment and reservoir management, high efficacy in water treatment, water reclamation from wastewater, and seawater reverse osmosis membrane desalination in addition to water conservation.

Water reclamation has been proven to be a better alternative to seawater desalination with half the capital cost and one-fourth the energy running cost. Water reclamation with stringent treatment processes that are combinations of microfiltration, reverse osmosis and ultraviolet has been practiced in many countries and regions (van Riper and Geselbracht 1999; Reith and Birkenhead 1998; Otaki et al. 1998; Loge et al. 1998), where there are constant water shortages. Reclaimed water is becoming an important part of the Singapore government strategy to expand the country's source of water supply. By 2012, it is expected to meet 15-20% of Singapore's water demand. Industrial use of reclaimed water frees large amounts of water for potable purposes.

Ultraviolet (UV) light is well known as a proven environmentally friendly technology for water disinfection (Sharpless and Linden 2001; von Sonntag and Schuchmann 1992). Irradiation with UV light at sufficient fluence (UV dose) results in irreparable damage to genetic materials (Clancy et al. 2000). The reproduction of the microorganisms by cell division is prevented, and the organisms lose their pathogenic character and eventually die. This process occurs within seconds and, in contrast to chemical disinfection, produces no harmful by-products. Therefore, it is particularly suitable for application in

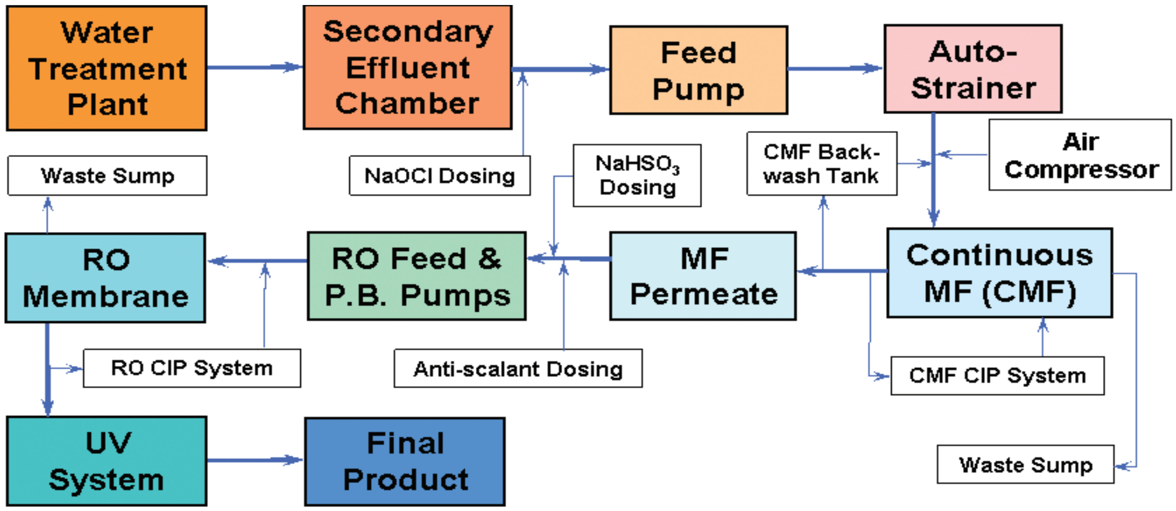

Figure 1: Block diagram of the water reclamation from secondary effluent (the MF can be either the Continuous Microfiltration system or the submersed suction microfiltration system and the UV system either the low pressure high output or the medium pressure unit)

water reclamation from wastewater or water treatment processes where concentrations of precursors of chemical disinfection by-products are normally high.

UV APPLICATION IN WATER RECLAMATION

In water reclamation from the secondary effluent under tropical conditions, the effluent undergoes stringent purification and treatment process – using advanced dual-membrane [i.e., microfiltration (MF) and reverse osmosis (RO)] and UV technology. Figure 1 presents the main unit operations of the treatment process. Variations were allowed among the plants as they were designed and constructed by different contractors at different times and locations. The combinations of there unit operations had been installed in various water reclamation processes worldwide (Otaki et al. 1998; Loge et al. 1998; van Riper and Geselbracht 1999; Reith and Birkenhead 1998).

In this treatment process (Figure 1), multi-barriers are in place to prevent contaminants from entering the final product (Figure 2). The MF removes most of the turbidity, protozoa, bacteria, large particles of particulates and viruses. The RO membrane retains all types of the contaminants, including turbidity, protozoa, bacteria, viruses, particulate, organic and inorganic substances. The in-line ultraviolet (UV) disinfection units after the RO units provide additional safeguard against virus, bacteria, protozoa and enzymes if the integrity of the RO membranes were compromised.

DEMONSTRATION AND FULL-SCALE PLANTS

A demonstration study was undertaken with a 10,000 m^3 per day plant to confirm the performance of the combined unit operations. Successful operation of the demonstration plant brought forward construction of three full scale plants (Table 1) with similar unit operations. The total

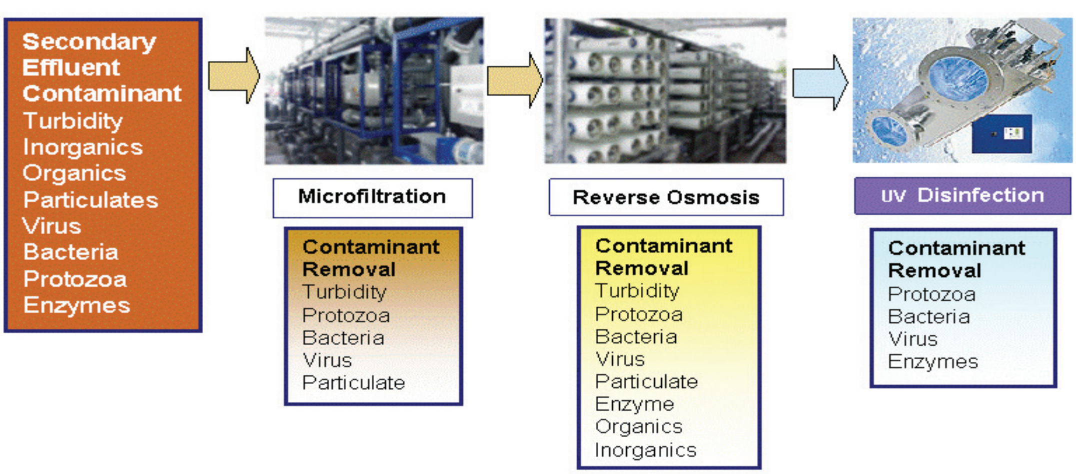

Figure 2: Multi-barrier approach for removal of contaminants in water reclamation process. Different MF, RO and UV systems might be employed according to local condition

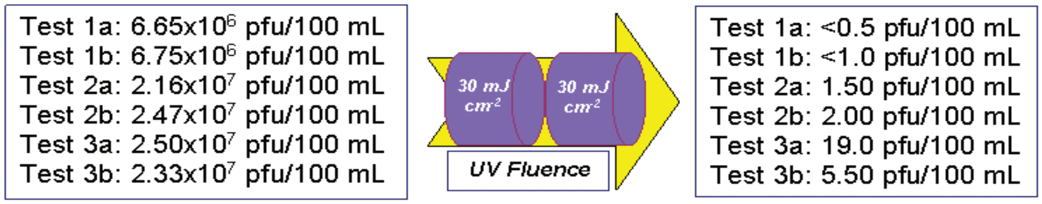

Figure 3: UV disinfection challenge tests with MS-2 colliphage surrogate at flow rate of 200 m^3 hr^{-1} (modified from Poon 2002)

capacity of the three plants is 96,000 m^3 per day. A fourth one, which will be constructed and operated by the private sector, is currently going through the tendering process.

Two types of UV systems were selected for the three water reclamation plants. A low pressure high output UV system was chosen for one plant, and a medium pressure system for the other two plants. The UV systems have features of remote operation, UV dose control and automatic sleeve wiping to allow the plants to operate unmanned.

The design criteria are listed in Table 2. Proper operation of the plants delivers a fluence (UV dose) greater than 60 mJ cm^{-2} (600 J m^{-2}) at the end of UV lamp life and ensures at least 4-log reduction of microorganisms on disinfection

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HIGH QUALITY WATER

Studies using the demonstration plant showed that the MF and RO removed the contaminants completely and produced a high quality final product (Table 3) with pathogenic organisms non-detectable (i.e., <1 cfu per 100 mL) (Table 4). UV disinfection challenge studies were therefore conducted. The MS-2 colliphage surrogate was used in the challenge studies with the target of a fluence (UV dose) of 60 mJ cm^{-2} (600 J m^{-2}). The results from repeated studies show that the inactivation was >7 log at a water flow rate of 10,000 m^3 per day (Figure 3). It was concluded that the multi-barrier water reclamation plants with unit operations of MF, RO and UV can ensure high water quality standard in terms of removal of viruses, bacteria and protozoa. The three full scale plants showed the same per-

Table 1: Capacities of water reclamation plants and UV systems employed after the RO member unit operation

Water Reclamation Plant	Capacity (m^3 per day)	UV System	In Operation Since
A	32,000	2+1 units of PHOTON® Medium Pressure System	January 2003
B	40,000	2+1 units of PHOTON® Medium Pressure System	December 2002
C	24,000	BX 1200, Spektrotherm® HP lamps, Low Pressure High Output	May 2004
D	40,000	To be determined	2006

Table 2: Design criteria for ultraviolet system for disinfection in water reclamation

	Water Reclamation Plant			
Design Parameters	A	B	C	Remarks
UN Units	2+1	2+1	2+1	UV system is placed after the train of an automated strainer, MF and RO membrane unit operations.
Lamps per Unit	2	2	4	
Lamp Life Span (hours)	35,000	35,000	80,000	
Feed Flow Rate (m^3 h^{-1} per unit)	1,000	1,000	1,000	
Max Feed Pressure (kPa)	100	100	100	
$UV_{253.7}$ Transmittance (%)	90	90	90	
Min. Fluence (UV Dose) (mJ cm^{-2})	60	60	90	
Virus Reduction (log)	>4	>4	>4	
Bacteria Reduction (log)	>4	>4	>4	

Table 3: Design criteria for ultraviolet system for disinfection in water reclamation[1]

Water Quality Parameters	Reclaimed Water	USEPA/WHO Standards
	Physical	
Turbidity (NTU)	<5	5 / 5
Color (Hazen Units)	<5	15 / 15
Conductivity (μS/cm)	<200	Not Specified (– / –)
pH	7.0 - 8.5	6.5-8.5 / –
Total Dissolved Solids (mg/L)	<100	500 / 1000
Total Organic Carbon (mg/L)	<0.5	– / –
Total Alkalinity ($CaCO_3$) (mg/L)	<20	– / –
Total Hardness ($CaCO_3$) (mg/L)	<20	Not available
	Chemicals (mg L^{-1})	
Ammonium nitrogen (as N)	<0.5	– / 1.5
Chloride (Cl)	<20	250 / 260
Fluoride (F)	<0.5	4 /1.5
Nitrate (NO_3)	<16	– / –
Silica (SiO_2)	<3	– / –
Sulfate (SO_4)	<5	250 / 250
Residual Chlorine (Cl, Total)	<2	– / 5
Total Trihalomethanes	<0.08	0.08 / –
	Metals (mg L^{-1})	
Aluminum (Al)	<0.1	0.05–0.2 / 0.2
Barium (Ba)	<0.1	2 / 0.7
Boron (B)	<0.5	2 / 0.7
Calcium (Ca)	<20	– / –
Copper (Cu)	<0.05	1.3 / 2
Iron (Fe)	<0.04	0.3 / 0.3
Manganese (Mn)	<0.05	0.05 / 0.5
Sodium (Na)	<20	– / 200
Strontium (Sr)	<0.1	– / –
Zinc (Zn)	<0.1	5 / 3
	Bacteriological	
Total Coliform Bacteria (cfu per 100 mL)	Not detectable	Not detectable
Enterovirus	Not detectable	Not detectable

1 Source: Ong et al. (2002).

formance as the demonstration plant in terms of quality of the reclaimed water.

Due to its high quality, the reclaimed water may readily be conveyed to a wide range of users after post treatment. One need only restore the acid-alkali and/or pH balance to prevent water quality from being deteriorated. Uses of such reclaimed water include:

- General industrial use (washing and cleaning)
- Ultra-pure water production (Tan and Seah 2004; Viswanath et al. 2003)
  - – Wafer fabrication processes
  - – Semiconductor fabrication
- Cooling towers in air conditioning systems
- Makeup of the local water reservoir for drinking water production.

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Table 4: Summary of reclaimed water microbiological results at the demonstration plant (Ong et al. 2002)

Parameter	Unit	Min	Max	Mean	No. Samples	No. Detectable	No. Non-Detectable
Faecal Coliforms	cfu / 100 mL	ND	ND	NC	99	0	99
Total Coliforms	cfu / 100 mL	ND	ND	NC	99	0	99
HPC	cfu / 100 mL	1.1	80	52	97	80	17
Coliphagesomatic[1]	pfu / 100 mL	ND	ND	NC	87	0	87
Coliphate-male specific[1]	pfu / 100 mL	ND	ND	NC	87	0	87
Enterococcus	cfu / 100 mL	ND	0.2	NC	99	1	98
Clostridium perfringens	cfu / 100 mL	ND	ND	NC	91	0	91
Giardia	cyst / 100L	ND	ND	NC	16	0	16
Cryptosporidium	oocyst / 100L	ND	ND	NC	17	0	17
Enterovirus	present/absent	-	-	absent	21	0	21

1. These parameters are additional to those listed in the USEPA and WHO stndard/guidelines.

2 ND = Not detectable; NC = Not calculated.