A pilot-scale study on ultraviolet disinfection system for drinking water

Sun Wenjun and Liu Wenjun

ABSTRACT

In recent years, ultraviolet technology for drinking water disinfection has experienced rapid growth in North America and Europe, driven by the needs of disinfection by-product reduction and control of emerging pathogens such as *Cryptosporidium* which are resistant to chlorination. Tsinghua University has performed some work based on a pilot-scale UV system in Dongguan. The aim of this study was to evaluate the efficacy of UV systems for drinking water under pilot-scale conditions (continuous flow system) and to compare with the collimated-beam results in the laboratory for the same water quality. The experiment results showed that (1) UV was effective against *E. coli* and TBC. *B. substilis* and MS2 were more UV-resistant, especially when UVT was below 90%. (2) The inactivation of micro-organisms by UV could be described by first-order kinetics using fluence–inactivation data from laboratory studies in CB tests for a certain fluence range. No inactivation at low fluences (shoulder) and no further increase of inactivation at higher fluences (tailing) was observed for some challenge micro-organisms. (3) Water quality and UV sensitivity of the micro-organism influenced the inactivation rate. (4) For the daily monitor results of 13,000 h, UV could be a stable disinfection manner for total coliform and TBC. (5) The lamp intensity online monitor showed that the lamp efficiency decay was limited to within the first 12,000 h.

Key words | bioassay, drinking water disinfection, inactivation, UV irradiation

Sun Wenjun (corresponding author)
Liu Wenjun
Department of Environmental Science and Engineering,
Tsinghua University,
Beijing 100084,
China
E-mail: *sunwj05@mails.tsinghua.edu.cn*

INTRODUCTION

Ultraviolet (UV) disinfection has grown in acceptance as a primary disinfection process for drinking water since its efficacy in deactivating *Cryptosporidium* and *Giardia* was first revealed (Craik *et al.* 2000; Zimmer *et al.* 2003). Chemical disinfection with chlorine is ineffective against these pathogens. UV is now regarded as broadly effective against all pathogens, bacteria, protozoa and viruses that can be transmitted through drinking water(Chang *et al.* 1985; Hijnen *et al.* 2006). A multi-barrier strategy protects public health and UV has become an essential part of the treatment strategy for protection against microbial contamination and reduction of disinfection by-products (DPB). Nonetheless, the application of UV technology for drinking water is still in its stages of infancy in China. Tsinghua University established a UV disinfection pilot-scale system with a capacity of 25 m^3/h for drinking water treatment in Dongguan, Guangdong Province.

In drinking water treatment, UV inactivation for *E. coli*, *B. subtilis* and MS2 bacteriophage has already been studied by many researchers. *E. coli* has been proven to be very UV sensitive while *B. subtilis* is UV resistive (Chang *et al.* 1985; Mamane-Gravetz & Linden 2004). MS2 is the standard challenge organism for bioassays because of its good linear relationship within 100 mJ/cm^2 (Sommer *et al.* 1998). In addition, many studies have used collimated beams (CB) in the laboratory. Pilot-scale research on the effects of UV disinfection for drinking water remains few. Many studies have focused more on HPC inactivation of UV. For our

doi: 10.2166/aqua.2009.086

study, we chose total bacteria counts (TBC) as a challenge organism parameter, and was regulated under the guidelines of the Drinking Water Regulation of China (GB5749-2006).

The aim of this study was to evaluate the efficacy of UV systems for drinking water under pilot-scale conditions (continuous flow (CF) system) and to compare with the CB results in the laboratory for the same water quality. For our experiments, we chose *Escherichia coli* (*E. coli*), *Bacillus subtilis* (*B. subtilis*), MS2 and TBC as the challenge micro-organisms. Moreover, UVT (the fraction of UV intensity transmitted through 1 cm path length of the sample), flow rate and UV sensitivity of micro-organism were considered in this study as the important influencing factors. The pilot-scale system operated for two years and the estimation of the reliability of UV lamps was another research project derived from this study.

MATERIALS AND METHODS

Experimental designs

Water quality and experiment system

The selected influent of the UV disinfection system was filtrated water from the Dongguan No. 4 waterworks system. The source of this water was the Dongjiang River. Table 1 shows the characterized parameters of the filtrated water.

The influent to the UV annular system was irradiated with three low-pressure UV lamps (Trojan Technologies, Canada). Table 2 presents the main parameters of the UV reactor.

The experimental system used in this study is shown in Figure 1. Water was pumped by a centrifugal pump through a ball valve to the UV disinfection unit from the $3\,m^3$ storage tank. The flow rate was adjusted to $15\,m^3\,min^{-1}$ by the valve and was kept constant throughout the experiment. Before the UV system, there were two solution pots used to add an experimental microbe and coffee for bioassay experiment. The UVT was measured using a UV spectrophotometer (P254C UV Photometer, Trojan Technologies).

Table 1 | Quality of the filtrated water as characterized by physical and chemical parameters

Parameter	Value
pH	6.4–6.8
UV absorbance at 254 nm (cm^{-1})	0.02–0.03
Turbidity (NTU)	0.2–0.3
UVT	92–96%
Total organic carbon ($mg\,L^{-1}$)	0.8–1.4
Temperature (°C)	22–29
COD_{Mn} (mg/L)	1–1.2

Table 2 | Parameters of Trojan swift SC B03

Parameter	Value
Reactor volume (l)	40
Flow rate (m^3/h)	10, 15, 20, 25
UV lamp output power (W)	3 lamps × 143 W = 429 W

UV collimated-beam exposure and bioassay procedure

For the case of the ideal "plug flow" situation with perfect radial mixing and no longitudinal mixing (never achieved in a real reactor), the applied UV dose (mJ/cm^2) may be calculated by multiplying the volume-averaged fluence rate by the reactor retention time in seconds. Such an "ideal UV dose" is a maximum for a given reactor. In practice, UV doses are determined by bioassay, in which a suspension of a test organism (e.g. *Bacillus subtilis* or MS2 coliphage) was injected upstream of the UV reactor and samples taken downstream. The ratio of the active cell counts of the effluent samples to that of the influent samples is then compared with a dose–response curve determined in a collimated-beam apparatus to obtain the "reduction equivalent UV dose".

A dose–response curve can be developed by counting the number of surviving organisms at various doses using a bench-top collimated-beam apparatus. Specific microbial inactivation kinetics can therefore be developed based on this curve. The dose–response curve is important in calibrating for the reactor disinfection performance.

The standard UV dose measurement and calculation methods for collimated-beam experiments were followed as described by Bolton & Linden (2003). The samples were contained in 6 cm Petri dishes and gently stirred using a 1 cm long magnetic stirring bar during the exposures. The samples were transferred from the jars to the Petri dishes using sterile wide-bore pipettes. The distribution of UV

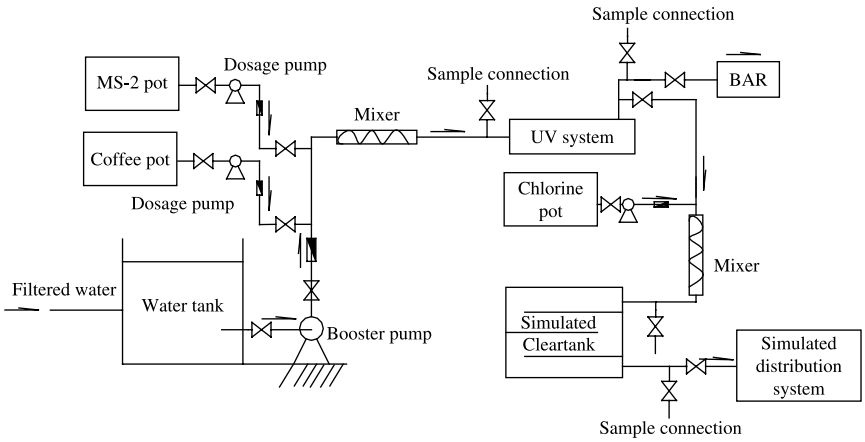

Figure 1 | Diagram of the experimental system.

intensity across the exposure surface was measured using a radiometer equipped with a sensor, and was incorporated into the average UV dose calculation, as described in detail in Bolton & Linden (2003). The UV intensity was 0.24 mW/cm^2 at the center of the exposure surface.

Analytical method

Microbiological preparation and counting method

The experiment used *E. coli* (ATCC1.3373) and *Bacillus subtilis* (ATCC6633), which were both provided by the Microbiology School of the Chinese Academy of Sciences. To prepare the test suspension, *E. coli* (1.3373) was inoculated into a flask containing 100 ml of nutrient broth (CM1, Oxoid Ltd), and this was incubated at 37°C on a shaker (100 rev/min) for 18 h to reach the stationary phase with a cell concentration of approximately 10^9 cells ml^{-1}. Similarly, the inoculated *Bacillus subtilis* was incubated at the same condition for 24 h and the peak concentration would achieve 10^8 cells ml^{-1}.

Spores of *B. subtilis* (ATCC6633) were cultivated on agar plates and termed "surface spores" (S6633) in this paper. The cultivation process consisted of streaking liquid-cultivated *B. subtilis* ATCC6633 on Columbia agar plates (Oxoid CM 331) prepared with 1% $CaCl_2$ for 24 h to ensure isolated colonies (Bolton & Linden 2003). Individual colonies were then inoculated into liquid tryptic soy broth (Oxoid CM 129), and after 4–5 h of incubation, the bacteria were inoculated onto Columbia plates and left to re-sporulate for 7 d at 37°C. Spores were collected and harvested by washing with sterile, deionized water three times, at 5,000 g for 15 min. The suspension was placed in a water bath at 80°C for 10 min to destroy the remaining vegetative cells and was refrigerated at 4°C. The spore concentrations (of nonirradiated and UV irradiated samples) were determined after serial tenfold dilutions, using the pour plate technique with PC-Agar (Oxoid CM 325), at 37°C for 2 d, as colony-forming units (CFU) per mL. The purity of sporulation was between 90–95% as tested by phase contrast microscopy.

E. coli concentration was measured using the APHA standard method 9222 (Bohrerova *et al.* 2006) which involves membrane filtration. Serial dilutions of irradiated and control samples were performed. The samples were cultured on Fuchsine sodium sulfite broth medium, and the number of colonies was counted after a 24 h incubation period using the most probable number (MPN) counting method. The dose–response curves were generated as a plot of the number of colony-forming units (CFU) per 100 mL of the samples versus the applied dose of UV.

Table 3 | Enumeration media and incubation times for microbial indicators

Micro-organism	Enumeration medium	Incubation time (h)
E. coli	Fuchsine sodium sulfite broth	24
*Bacillus subtilis**	Nutrient broth	24
TBC	Nutrient broth	24
MS2	TYGA	10

**Bacillus subtilis* was determined after pretreatment for 10 min in a water bath at 80°C.

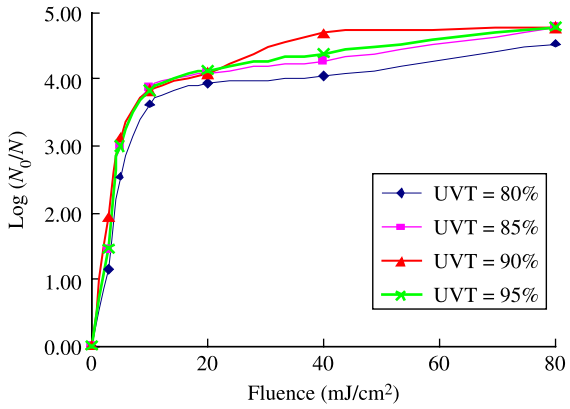

Figure 2 | *E. coli* inactivation by CB test.

MS2 bacteriophage (ATCC 15597-B1) was cultivated and enumerated with the double agar layer technique (Bolton & Linden 2003) using the host strain *Escherichia coli* (ATCC15597). A filtered portion of MS2 stock suspension with a concentration of 10^{10}–10^{11} plaque-forming units (PFU) per milliliter was diluted for UV inactivation experiments. The MS2 concentrations (of nonirradiated and UV irradiated samples) were determined after serial tenfold dilutions as PFU per milliliter. The enumeration method was modified by adding X-Gal (a chromogenic substrate for the detection of the enzyme betagalactosidase) to the bottom layer, which improved the counting of the plaques.

TBC was cultured using the method prescribed by the guidelines of the Drinking Water Regulation of China (GB5749-2006). The growth media and the incubation conditions for counting are listed in Table 3.

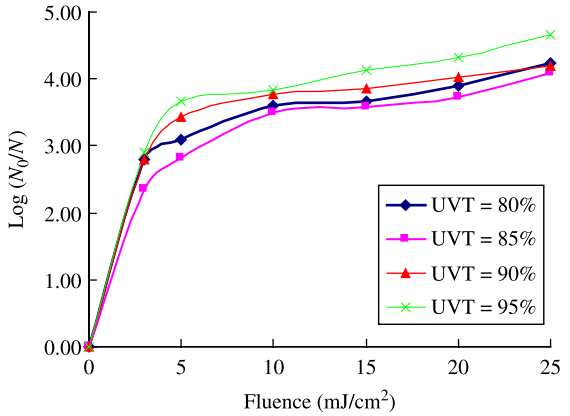

Figure 3 | TBC inactivation by CB test.

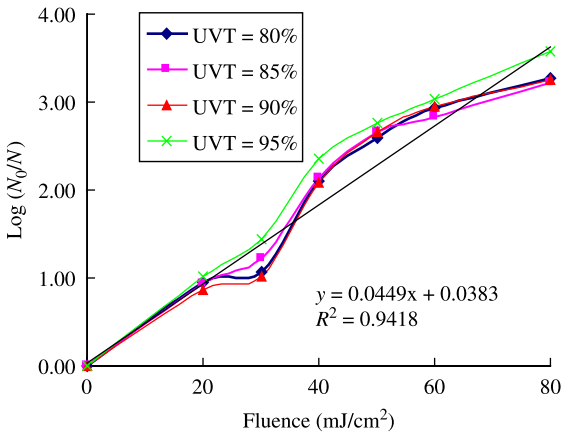

Figure 4 | *B. subtilis* inactivation by CB test.

Inactivation kinetics of the micro-organisms

The UV sensitivity of the selected micro-organisms is described by the parameters of inactivation kinetics. Inactivation is defined as the reduction of the concentration of culturable micro-organisms N due to the exposure to a concentration disinfectant C during a specific contact time t. The inactivation kinetics for chemical disinfectants is most commonly described by the first-order disinfection model of Chick (1908) and Watson (1908); the same model can be applied for UV disinfection. The inactivation of microorganisms is usually described by the log inactivation of N. Based on the first-order model, the linear relationship between log inactivation and the UV dose or fluence is described by

$$\log\left(\frac{N_t}{N}\right) = -k_a \,\text{Fluence} \tag{1}$$

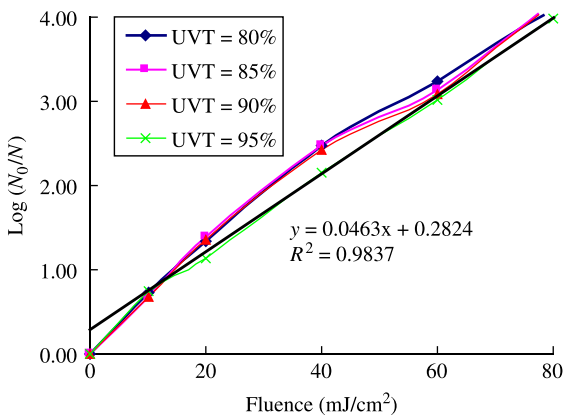

Figure 5 | MS2 inactivation by CB test.

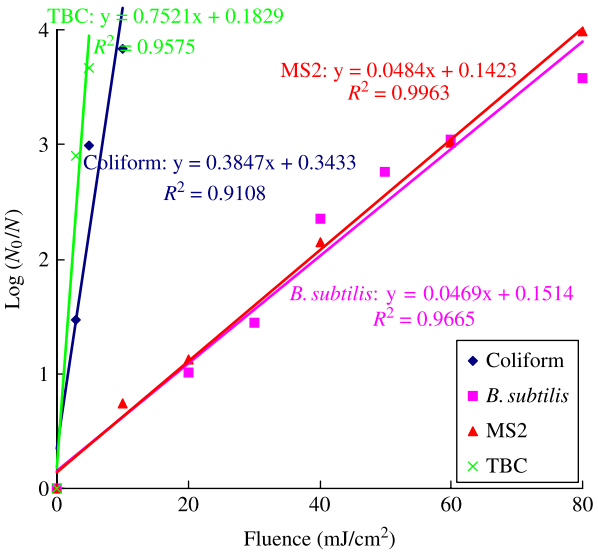

Figure 6 | Bench scale LP UV fluence–response curves for *E. coli*, TBC, MS-2 and *B. subtilis*.

where *Nt* is the microbial concentration after contact time *t*. Fluence is the product of the UV fluence rate (mW/cm^2) and the exposure *t* (mWs/cm^2 = mJ/cm^2) (Hijnen *et al.* 2006).

RESULTS AND DISCUSSION

The inactivation of UV for micro-organisms

UV inactivation for microbe under CB tests

For the CB test, the inactivation rate of *E. coli* was revealed to be proportional to the radiation dose until it reached a "plateau" region (Figure 2) when the dose exceeded 10 mJ/cm^2. Once the rate exceeded 20 mJ/cm^2, the inactivation rate only increased very slowly.

The inactivation rate of TBC was proportional to the radiation dose when the dose was below 25 mJ/cm^2 (Figure 3). The response curve achieved tailing when the UV fluence was above 5 mJ/cm^2.

B. subtilis were clearly less sensitive to UV than *E. coli* and TBC for the aerobic spores. In the CB test, the inactivation rate increased with the fluence linearly if the fluence was less than 80 mJ/cm^2. Hence, *B. subtilis* was fit for bioassay (Figure 4).

Table 4 | UV inactivation for typical organisms under CF system

		Log reduction (N_0/N_d)			
UVT	**Flow rate**	***E. coli***	**MS2**	***B. subtilis***	**TBC**
80%	10	5.99(0.12)	1.82(0.04)	3.14(0.07)	3.89(0.02)
	15	5.15(0.16)	1.67(0.02)	2.16(0.06)	3.66(0.08)
	20	4.04(0.09)	1.54(0.03)	1.80(0.04)	2.96(0.07)
	25	3.71(0.04)	1.41(0.03)	1.23(0.08)	2.72(0.09)
85%	10	6.07(0.14)	2.27(0.10)	4.14(0.16)	3.96(0.12)
	15	5.42(0.06)	1.86(0.11)	3.19(0.08)	3.74(0.05)
	20	4.66(0.15)	1.73(0.08)	2.94(0.08)	3.49(0.13)
	25	4.48(0.05)	1.61(0.09)	2.12(0.08)	3.26(0.09)
90%	10	6.41(0.14)	2.92(0.13)	4.70(0.06)	4.20(0.08)
	15	5.52(0.08)	2.30(0.08)	3.77(0.03)	3.87(0.07)
	20	5.09(0.07)	2.03(0.03)	3.00(0.03)	3.63(0.05)
	25	4.71(0.09)	1.75(0.07)	2.63(0.10)	3.35(0.03)
95%	10	6.38(0.14)	4.24(0.16)	4.92(0.15)	4.24(0.09)
	15	5.66(0.16)	3.70(0.10)	4.54(0.06)	3.94(0.07)
	20	5.33(0.06)	3.11(0.07)	3.98(0.06)	3.87(0.07)
	25	4.88(0.09)	2.62(0.09)	3.54(0.11)	3.71(0.03)

MS2 was the standard challenge organism for the bioassay. For the CB test, the inactivation rate was 2 log(N_0/N) with the fluence of 40 mJ/cm^2 (Figure 5).

Kinetics of UV inactivation

Much of the inactivation data can be adequately described using the first-order disinfection model (Figure 6), at least for a certain fluence range. An offset UV fluence before inactivation starts, i.e. a shoulder model, was observed for *Bacillus* spores (Bohrerova *et al.* 2006). The simple inactivation model, wherein the shoulder was given as an offset of the first-order model, was used in this study. Another deviation from first-order kinetics is the reduction of the inactivation rate at higher UV fluences (tailing). This was observed clearly in the CB tests using *E. coli*. Tailing normally started after at least 99% of the initial available micro-organisms had been inactivated and was observed to a larger extent in the more UV susceptible micro-organisms (Mamane-Gravetz *et al.* 2005). For the more resistant organisms (MS2), tailing was not evidently observed. Nonetheless, the cause

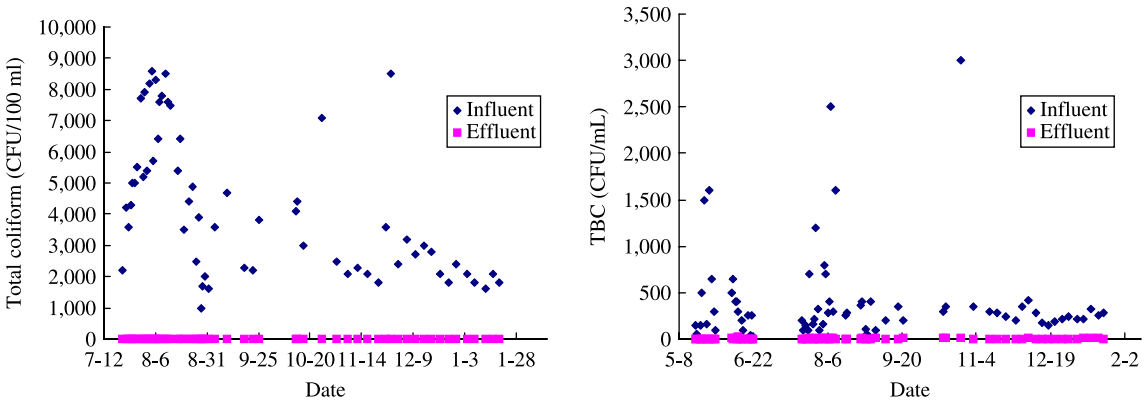

Figure 7 | The results of daily monitoring for total coliform (left) and TBC (right).

of tailing remains a subject of debate. Several causes have been hypothesized, such as experimental bias, hydraulics, aggregation of micro-organisms or a resistant subpopulation; however, no conclusive evidence is available for any of these.

For micro-organisms where tailing is observed (*E. coli* and TBC), we used the first-order model only for the fluence range that yielded a linear relation with the inactivation in the experiments. The fluence range was $0-5\,mJ/cm^2$ for TBC and $0-10\,mJ/cm^2$ for *E. coli*. Because of the observed tailing, extrapolation of this inactivation rate to higher fluences yielded uncertain results. For use in quantitative microbiological risk assessment (QMRA) (Clesceri *et al.* 1998), the higher fluences were assumed to yield (at least) the same inactivation credits as the highest fluence in the linear relationship (Hijnen *et al.* 2006).

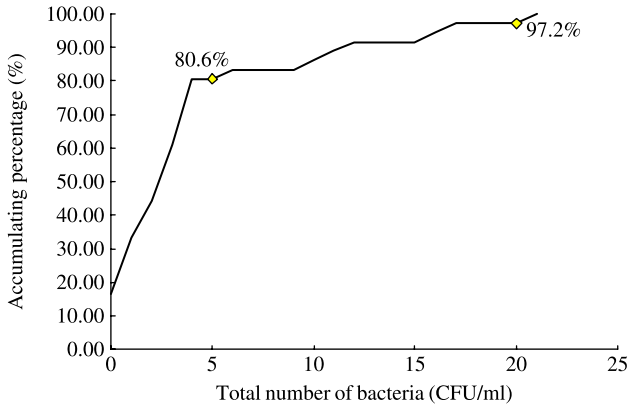

Figure 8 | Accumulating percentage of TBC.

UV inactivation for micro-organism under CF system

In the CF system, the inactivation rate was much higher than some other reported results (Hijnen *et al.* 2006). The UV disinfection system had a 3-log inactivation rate for *E. coli* with the flow rate of $25\,m^3/h$ and UVT of 80% (bioassay fluence = $60\,mJ/cm^2$) (Table 4).

The changes in the inactivation rate with the flow rate were not evident when the UVT was higher than 85%. This phenomenon could be attributed to the broad inactivation effect of UV for different micro-organisms.

Table 5 | Required fluence for *E. coli*, TBC, *B. subtilis* and MS2

	Required fluence (mJ/cm^2)			
Bacteria	**1**	**2**	**3**	**4**
E. coli	1.87	4.71	7.55	10.40
TBC	1.09	2.42	3.75	5.08
B. subtilis	18.09	39.42	60.74	82.06
MS2	17.72	38.38	59.04	79.70

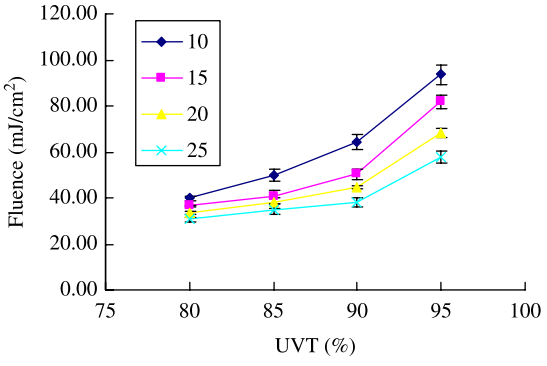

Figure 9 | The UV fluence-transmittance curve for *B. subtilis* in the CF system.

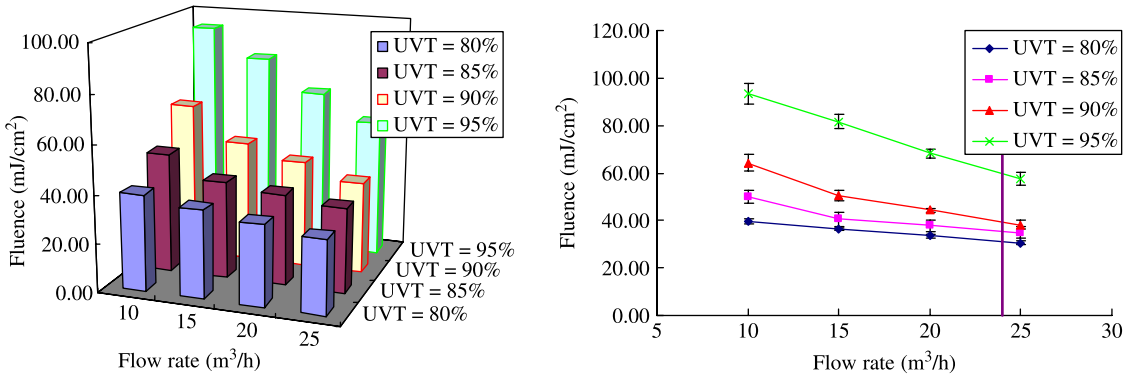

Figure 10 | UV fluence–flow rate curve for *B. subtilis* in CF system.

Daily monitoring for total coliform counts and TBC detection

The daily detection of *E. coli* and TBC can be used for evaluation of the practical disinfection effect of the UV system. Figure 7 shows that the total coliform and total bacteria counts of effluent satisfied the guidelines of the Drinking Water Regulation of China (GB5749-2006). In many of these situations, the total coliform of the effluent was not detected and the TBC was under 25 CFU/mL, which was far fewer than the regulations (< 100 CFU/mL).

The TBC had an 80.6% guarantee rate of less than 5 CFU/ml and a 97.2% guarantee rate of less than 20 CFU/mL (Figure 8). Several studies have reported an increased UV resistance of environmental bacteria and bacterial spores, as compared to lab cultured organisms. We detected a similar phenomenon in this experiment. Even the influent TBC is not very high (100–1,000 CFU/mL), and there were still some TBC detected (0–20 CFU/mL) in the effluent with a UV dose of 60 mJ/cm^2. This might be related to some resistant bacteria in the environment or the reactor's hydraulic characteristics.

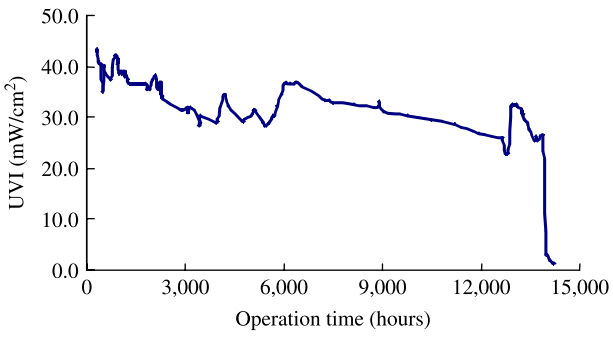

Figure 11 | UV intensity decline curve in CF system.

Influencing factors of UV disinfection system

UV sensitivity of micro-organisms

UV sensitivity of *E. coli*, *Bacillus subtilis* and TBC determined with CB tests are shown in Table 5. *B. subtilis* and MS2 required about 80 mJ/cm^2 for 4-log inactivation.

UVT

The presence of UV absorbing organic and inorganic compounds in water will reduce UV fluence. As Figure 9 demonstrates, there was less impact of UVT on the fluence of the CF system when the flow rate was high.

Flow rate

Figure 10 shows that the fluence assessed under the same experimental conditions was more sensitive to the changes in flow rate than UVT. The UV fluence changed little when the UVT was adjusted to 80% and 85%, repsectively. In contrast, the impact of flow rate on UV dose was more evident at the UVT of 90% or 95%, respectively. The right figure shows that the bioassay UV dose was a little lower than the designed value. Also, when the flow rate was 20 or 25 m^3/h, the changes of fluence was not evident. This finding might suggest that the flow rate would become the main factor in ensuring UV fluence when flow rates are low.

The decline in intensity of the UV lamp

The decline of UV intensity (UVI) in online monitoring was proven an important factor in the impact of the disinfection effect of the UV system (Figure 11). The UVI fluctuated from 30–40 mW/cm^2 in the first 6,000 h and then decreased smoothly later. When the operational time reached 13,800 h, the UVI suddenly decreased to about 0. The UV lamp's life is 12,000 h with a margin of about ± 15%.

CONCLUSIONS

(1) The data on the inactivation kinetics of disinfection with UV irradiation demonstrate that the process is effective against the four challenge micro-organisms relevant for drinking water filtration practices. The inactivation of micro-organisms by UV could be described by first-order kinetics using fluence–inactivation data from laboratory studies in CB tests. No inactivation at low fluences (shoulder) and no further increase of inactivation at higher fluences (tailing) was observed for some micro-organisms.

(2) *B. subtilis* was highly UV resistant in this experiment. Bacteria are more susceptible with a fluence requirement of 20 mJ/cm^2 for an inactivation rate of 3-log. As our daily monitoring results have shown, the effluent of environmental *E. coli* and total number bacteria of the UV system were below the maximum for the Drinking Water Regulation of China.

(3) UVT, flow rate and UV sensitivity of the micro-organisms influenced the inactivation rate of the UV disinfection system. Also, there was less impact of UVT on the fluence of the CF system when the flow rate was low.

(4) The lamp intensity online monitor showed that the lamp efficiency decay was limited to within the first 12,000 h. When the operational time reached 13,800 h, the UVI suddenly decreased to about 0. The UV lamp's life is 12,000 h with a margin of about ± 15%.

ACKNOWLEDGEMENTS

This study was funded by the Dongguan Government and Dongjiang Water Affairs Company, Ltd. Trojan Technology Inc. provided much technical information, while both Dongjiang Water Affairs Company, Ltd. and Trojan Technology Inc. provided considerable assistance during the experimental period. We likewise express our gratitude to all individuals who provided help during the course of this work.

REFERENCES

Bohrerova, Z., Mamane, H. & Ducoste, J. 2006 Comparative inactivation of *Bacillus subtilis* spores and MS-2 coliphage in a UV reactor: implications for validation. *J. Environ. Eng.* **132**(12), 1554–1561.

Bolton, J. & Linden, K. 2003 Standardization of methods for fluence (UV dose) determination in bench-scale UV experiments. *J. Environ. Eng.* **129**(3), 209–215.

Chang, J., Ossoff, S., Lobe, D., Dorfman, M., Dumais, C., Qualls, R. & Johnson, J. 1985 UV inactivation of pathogenic and indicator micro-organisms. *Appl. Environ. Microbiol.* **49**(6), 1361–1365.

Chick, H. 1908 An investigation of the laws of disinfection. *J. Hyg.* **8**, 92–158.

Clesceri, L., Greenberg, A. & Eaton, A. 1998 *Standard Methods for the Examination of Water and Wastewater*, 20th edition. American Public Health Association, Washington, DC.

Craik, S., Finch, G. & Bolton, J. 2000 Inactivation of Giardia muris cysts using medium-pressure ultraviolet radiation in filtered drinking water. *Water Res.* **34**(18), 4325–4332.

Hijnen, W., Beerendonk, E. & Medema, G. 2006 Inactivation credit of UV radiation for viruses, bacteria and protozoan (oo)cysts in water: a review. *Water Res.* **22**(3), 3–4.

Mamane-Gravetz, H. & Linden, K. 2004 UV disinfection of indigenous aerobic spores: implications for UV reactor validation in unfiltered waters. *Water Res.* **38**(12), 2898–2906.

Mamane-Gravetz, H., Linden, K., Cabaj, A. & Sommer, R. 2005 Spectral sensitivity of Bacillus subtilis spores and MS2 Coliphage for validation testing of ultraviolet reactors for water disinfection. *Environ. Sci. Technol.* **39**(20), 7845–7852.

Sommer, R., Haider, T., Cabaj, A., Pribil, W. & Lhotsky, M. 1998 Time fluence reciprocity in UV disinfection of water. *Water Sci. Technol.* **38**(12), 145–150.

Watson, H. E. 1908 A note on variation of the rate of disinfection with change in the concentration of the disinfectant. *J. Hyg.* **8**, 536–542.

Zimmer, J., Slawson, R. & Huck, P. 2003 Inactivation and potential repair of *Cryptosporidium parvum* following low- and medium-pressure ultraviolet irradiation. *Water Res.* **37**(14), 3517–3523.

First received 10 November 2008; accepted in revised form 30 January 2009