Evaluation of UV Disinfection Performance in Recirculating Systems

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ABSTRACT

The use of ultraviolet (UV) disinfection devices has become increasingly popular in wastewater and aquaculture industries. Although the effectiveness of UV disinfection has been well documented for flow-through operation regimes in wastewater treatment, research focusing on water recirculating systems is still limited. In this study, the performance of single-lamp UV devices were tested on a recirculating system for fecal coliform (FC) disinfection. Experimental results indicated that UV power input, recirculating flow rate and water UV transmittance were three important factors determining UV disinfection efficiency. An UV disinfection model for a recirculating system was developed based on theoretical analysis and experimental data. A key model parameter, namely the first-order inactivation rate constant (k), was determined to be 0.0062 $m^2 J^{-1}$ for FC disinfection. Simulation using the model provided useful information for design and operation of recirculating UV

disinfection systems. The model prediction of disinfection process for other microorganisms is also capable of using reported values of the inactivation rate constant.

INTRODUCTION

Ultraviolet (UV) disinfection is an increasingly popular alternative in wastewater treatment (Hanzon and Vigilia 1999) and aquaculture industries. Absorption of UV radiation causes damage to the genetic material of bacteria, which prevents cell replication (U.S. EPA 1986). The advantages of UV disinfection include being non-toxic, ecologically-friendly, effective with a wide range of organisms, requiring a short contact time, and being easy to control (Moreland et al. 1998; Hanzon and Vigilia 1999). The effectiveness of UV radiation to inactivate pathogenic microorganisms in wastewater has been well documented for wastewater treatment purposes (Johnson and Qualls 1984; U.S. EPA 1986; Darby et al. 1993; Emerick et al. 1999). UV facilities used in the wastewater industry are usually flow-through systems with several banks of lamps in series (Ho et al. 1998). Pathogen inactivation can be described as a first-order reaction with respect to UV dose usually defined as UV light intensity times the exposure time (U.S. EPA 1986). Various models have been developed to describe the response of microorganisms such as fecal coliforms (FC) to UV light to aid in the design of UV disinfection systems (Qualls and Johnson 1985; U.S. EPA 1986; Loge et al. 1996a, 1996b). However, these models were developed for flow-through UV disinfection systems used in the wastewater treatment industry.

UV devices have become an integral part of many recirculating aquaculture operations providing disinfected water to hatchery, rearing, and depuration operations. Recirculation is a major feature of these aquaculture systems, which makes the evaluation of UV disinfection effectiveness different from that in flow-through wastewater treatment systems. Recirculating systems have attracted significant attention in the last two decades for applications in aquaculture. Lack of suitable water supplies and more stringent control of waste and nutrient discharges from pond and raceway facilities drive the demand for recirculating systems. However, little research has been reported on UV disinfection

performance in recirculating aquaculture systems. Fish production generates wastes due to excretion and uneaten food. Without proper treatment, accumulation of these wastes will create unhealthy conditions that may result in reduced fish growth rates, low feed conversion efficiency, disease and elevated mortality. An UV unit for disease disinfection is an important component for a reliable recirculating system. Although significant research efforts have been devoted to recirculating systems in the last two decades (Timmons and Losordo 1994; Losordo 1998a, 1998b), studies focusing specifically on UV disinfection performance are scarce.

The objectives of this study were (1) to evaluate the performance characteristics of UV disinfection devices in recirculating systems under various conditions; (2) to develop an UV disinfection model for recirculating systems, (3) to calibrate model parameter and to validate the model using the experimental data, and (4) to simulate UV disinfection behaviors under various conditions to provide quantitative information for the design and operation of UV disinfection devices used in recirculating systems.

THEORETICAL ANALYSIS

UV radiation absorbed by the nucleic acid of bacteria can damage the genetic material and prevent cell replication (U.S. EPA, 1986). UV disinfection performance in terms of a concentration reduction rate has typically been described as a first-order reaction:

$$\frac{dN_t}{dt} = - kI_{ave}N_t \qquad (1)$$

where N_t = bacterial concentration (CFU per 100 ml) (CFU = colony forming unit); t = time (s); k = first-order inactivation rate constant (m^2 J^{-1}); I_{ave} = average UV intensity (W m^{-2}); For an initial bacterial concentration (N), integrating equation (1) gives a bacterial concentration after exposure to UV (N_t);

$$Nt = N\, e^{-kI_{ave}t} \qquad (2)$$

The average UV intensity inside an UV unit can be calculated using Beer's law (U.S. EPA 1986). For a cylindrical reactor with a single central lamp surrounded by a quartz tube (Fig. 1), the UV intensity at radius r can be expressed as:

$$I_r = \frac{PT_r^{100(r-r_o)}}{2\pi rL} \qquad (3)$$

The average UV intensity is thus obtained using the following equation:

$$I_r = \frac{\int_{r_o}^{R} I_r 2\pi rL\, dr}{V_L} = \frac{P}{100V_L \ln T_r} = (T_r^{100(R-r_o)} - 1) \qquad (4)$$

where P = output power of the UV unit (W); I_r = UV intensity at radius r (W m^{-2}); $T_r = UV_{254}$ (254 nm wave length) transmittance through water of one centimeter thickness (cm^{-1}); L = active length of the UV unit (m); V_L = total contact volume of the UV unit (m^3); R = radius of the inner surface of the UV unit cylinder (m); and r_o = radius of the quartz tube of the UV unit (m) (Fig. 1). For the tested 25-W and 40-W UV units in this study, R and r_o were 0.0254 m and 0.011 m, respectively.

Because an UV device behaves hydraulically as a plug-flow reactor (Darby et al. 1993), the average exposure time for a flow-through UV reactor can be determined by dividing the net reactor volume by the flow rate through the system. For flow through an UV unit, bacterial concentration of the treated water can be expressed as:

$$N_\tau = N \exp(-kI_{ave}VL/Q) = N \exp\left(-kP \frac{T_r^{100(R-r_o)} - 1}{100Q \ln T_r}\right) \qquad (5)$$

where N_τ = bacterial concentration of the flow through a working UV unit (CFU per 100 ml); Q = flow rate through the UV unit (m^3 /s).

For a recirculating system (Fig. 2), assuming bacterial concentration within a system is homogeneous, the bacterial storage or dissipation rate depends on the balance between the input rate from the source

production and the influent, and the output rate including effluent and reduction by the UV unit. The basic equation can be developed based on mass balance principle.

$$\frac{dN}{dt} = N_s + \frac{Q_e}{V}(N_i - N) - \frac{Q}{V}(N - N_r) \qquad (6)$$

where N_S = bacterial source production rate of the system (CFU per 100 ml), including excretion by fish and growth within the system; Q_e = water exchange rate ($m^3\ s^{-1}$); V = total water volume of the recirculating system (m^3); N_i = bacterial concentration of the influent (CFU per 100 ml).

At steady state, substituting equation (5) into equation (6) results in:

$$N = \frac{N_S V + Q_e N_i}{Q_e + Q\left\{1 - exp\left[-k \frac{P}{100 Q \ln T_r}(T_r^{100(R-r_o)} - 1)\right]\right\}} \qquad (7)$$

For a closed recirculating system ($Q_e = 0$) of UV disinfection, the following equation can be derived from equation (7).

$$\frac{N_s}{N} = \frac{Q}{V} = \left\{1 - exp\left[-\frac{k}{100 Q \ln T_r}\frac{P}{V}\frac{V}{Q}(T_r^{100(R-r_o)} - 1)\right]\right\} \qquad (8)$$

where the term N_S/N is defined as RSRR (relative specific reduction rate). Physically, the RSRR describes the ratio of the bacterial production rate to the equilibrium bacterial concentration in a system. A high value of the reduction rate implies a high disinfection efficiency. The value of Q/V represents the cycle rate of the water through an UV unit, and the ratio P/V gives the UV power input per cubic meter of water. Therefore, equation (8) describes UV disinfection efficiency as a function of water cycle rate, UV power input ratio and water UV_{254}

transmittance, which provides a better understanding of the performance of UV disinfection in a recirculating system.

MATERIALS AND METHODS

The UV disinfection study was conducted using a water recirculating system as shown in Fig. 3. The system consisted of a tank, a recirculating pump, and a single-lamp ultraviolet (UV) unit (Aqua Ultraviolet, CA, USA). Prior to each test, the tank was cleaned and filled with artificial seawater or freshwater (Table 1). The artificial seawater was made using Durex All Purpose Salt (Morton International, Chicago, USA) and de-chlorinated tap water. Wastewater containing a high concentration of microorganisms, collected from the wastewater lagoon of a nearby dairy farm was used as a bacterial source. For each test, one percent of dairy wastewater (v/v) was added into the water bath and mixed with the artificial seawater. An air diffuser was placed in the water bath to maintain dissolved oxygen (DO) concentration at 9.3±0.4 mg l^{-1} (measured using a YSI-50 DO meter, Yellow Springs, Inc., USA). The diffuser also served as a mixer to keep coliform concentration homogeneous within the water bath. The mixed water was pumped from the bath through a one-way valve, and then returned to the bath via two ways: an over flow path and a disinfection path through the UV unit (Fig. 3). One ball valve was used in each path to adjust water flow rates through the UV device according to the experimental protocol. Timing was started once the UV light was turned on. Water samples were collected from the water bath at different disinfection times (Table 1). Before each test, the outside surface of the quartz sleeve of the UV lamp was hand cleaned with commercial cleaning solution so that the effect of sleeve dirt on the disinfection efficiency was virtually eliminated. All of the treatments had a salinity of 15% except treatments 11 (fresh water) and 12 (26% salinity) (Table 1). Among the treatments, UV_{254} transmittance was adjusted by adding a different volume of wastewater. For all the treatments, temperature and pH were maintained at 13.2±2.0 °C and pH 8.15±0.20, respectively.

Sample analyses were performed in the Water Quality and Waste Analysis Laboratory at Washington State University. The bacterial species evaluated for UV disinfection performance was fecal coliform

Table 1 UV disinfection experiments performed in different conditions.

Treatment number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
UV unit power (W)	25	25	25	25	25	25	25	40	40	40	25	25
Wastewater volume (l)	340	340	340	340	340	340	340	340	340	340	680	680
Salinity (‰)	15	15	15	15	15	15	15	15	15	15	0	26
Flow rate (s^{-1})	1.26	1.26	1.26	2.52	0.63	1.26	2.52	2.52	1.26	1.26	1.26	1.26
TSS (mg l^{-1})	60	74	79	71	51	46	36	36	34	50	36	44
Turbidity (NTU)	13.7	16	32.1	31	14.5	9.4	17.1	15.9	15.7	28.3	29.2	28.8
UV_{254} transmittance (% cm^{-1})	54.2	52.9	30.1	25.3	57.6	69.2	52.1	38.2	39.4	26.8	35.0	31.0
Fecal coliform concentration (CFU per 100ml)												
Disinfection time = 0 (s)	32250	61400	72000	24500	22000	12500	14000	27500	27500	39000	67000	37000
270	19000	39000	48000	12500	13900	7500	10850	16250	15000	19000		
540	8900	27150	27500	8250	8500	3550	3900	4425	5150	8800	34800	29000
810	4800	8900	18800	5950	5500	1180	1550	1300	2300	3150		
1080								350	855	1500		
1350	2000	4050	6600	850	1900	220	400	90	355	895		
1890	375	700	1150	160	1070	60	80					
2160											6620	4460
2700											4940	1950

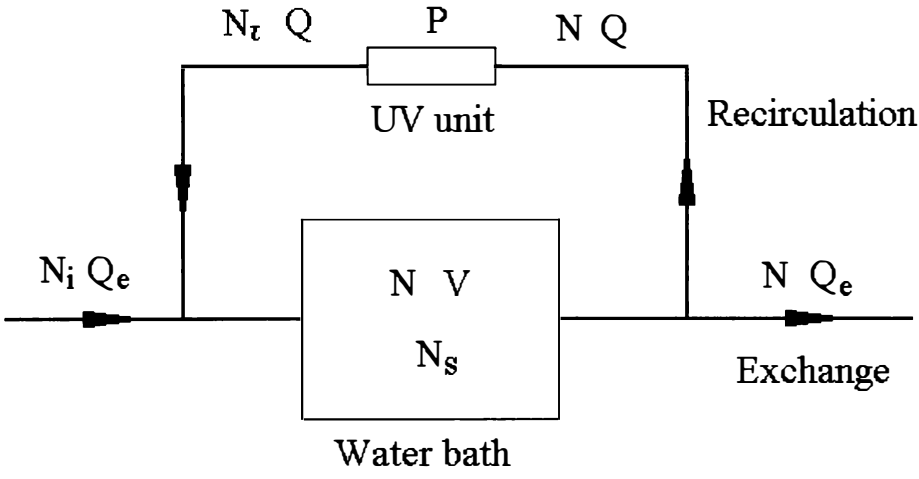


Figure 1. Schematic diagram of a recirculating system for UV disinfection.

(FC). The concentration of FC was determined using the membrane filter procedure specified by the Standard Method of 9222D (APHA 1995). It should be pointed out that fish do not excrete FC. The target for UV disinfection in most aquacultural systems is not FC, but other microorganisms. The reasons for selection of FC as an indicator of UV disinfection were: (a) it is a most common species studied for UV disinfection purposes; (b) a reliable standard method is available (APHA 1995); (c) FC is a target microorganism for depuration systems; (d) the results of this study provide information for reference and comparison with disinfection practices targeting other microorganisms. Initial water samples were collected before each trial (disinfection time = 0 as shown in Table 1). In addition to FC analysis, these samples were also analyzed for UV_{254} (UV light at a wave-length of 254 nm) transmittance using a Spectronic 21-D spectrophotometer (Milton Roy, Brussels, Belgium), turbidity using a 965-A Digital turbidimeter (Orbeco Analytical Systems, Inc., NY, USA), and total suspended solids (TSS) concentration according to the Standard method of 2540D (APHA 1995).

The UV units were highly effective for FC disinfection under all experimental conditions as presented in Table 1. In most cases, a 25-W UV unit disinfected about 99% of FC in the 340-liter wastewater within 31.5 minutes. This indicated that only about 1% FC remained after 7 cycles through a 25-W UV unit. Similarly, the system showed about

Figure 2. Cylindrical geometry of a single lamp UV unit.

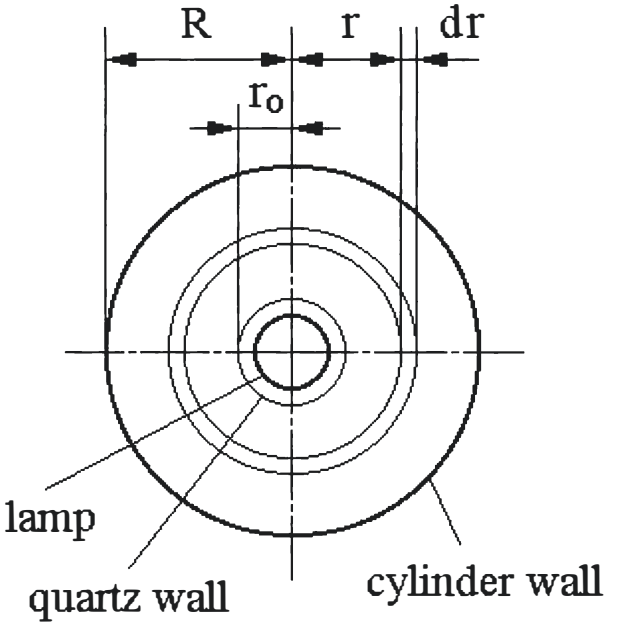


Figure 3. Schematic of the UV disinfection experimental system.

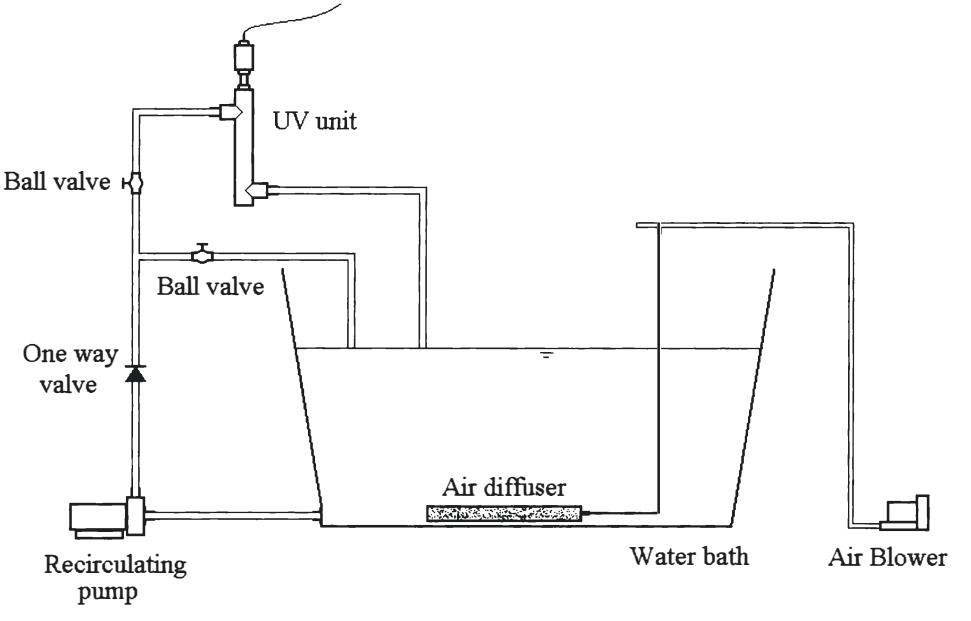


Table 2 Literature values of the inactivation rate constant for some microorganisms.

Microorganisms	Values of k (m^2 J^{-1}), Reference
Total coliform	0.0084-0.0166 (Ho et al. 1998)
Escherichia coli	0.0127 (Nieuwstad et al. 1991)
Fecal streptococci	0.0067 (Nieuwstad et al. 1991)
	0.0084 (Havelaar et al. 1987)
Spores of sulphite-reducing clostridia	0.0014 (Nieuwstad et al. 1991)
Somatic coliphages	0.0159 (Nieuwstad et al. 1991)
	0.0144 (Havelaar et al. 1987)
F-specific bacteriophages	0.0053 (Nieuwstad et al. 1991)
	0.0054 (Havelaar et al. 1987)
MS2 bacteriophages	0.0106 (Havelaar et al. 1990)
Reoviruses	0.0055 (Nieuwstad et al. 1991)

99% of FC removal efficiency after 5 cycles through a 40-W UV unit. The disinfection efficiency of treatment 5 was extremely low compared with those of the others due to the low flow rate. Treatments 11 and 12 were conducted for comparing the impact of salinity on the UV disinfection of fecal coliform. No significant difference ($R^2 = 0.92$, $N = 4$, $P < 0.05$) in the survival ratio was observed due to salination (Table 1). The results in Table 1 generally indicated that UV power, flow rate and UV_{254} transmittance were the three most important factors affecting UV disinfection efficiency.

MODEL PARAMETER CALIBRATION

The first-order inactivation rate constant (k) is a key parameter for the UV disinfection model, which was determined below using experimental data (Table 1). During the tests, there was no bacterial source ($N_S = 0$) and no water exchange ($Q_e = 0$) in the experimental system.

Equation (6) was thus simplified as:

$$\frac{dN}{dt} = \frac{Q}{V}(N - N_\tau) \qquad (9)$$

Integrating equation (9) and subtracting equation (5) gives following expression:

$$\frac{N}{N_o} = exp\{-\frac{Qt}{V}[1-exp(-kP\frac{T_r^{100(R-r_o)}-1}{100Q\,lnT_r})]\} \qquad (10)$$

where N_0 = initial fecal coliform concentration (CFU per 100 ml), and the value of N/N_0 represents survival ratio. To determine the rate constant k, equation (10) was changed into following form:

$$ln[1+\frac{V}{Qt}ln(\frac{N}{N_o})] = -k\frac{T_r^{100(R-r_o)}-1}{100Q\,lnT_r}P \qquad (11)$$

Linear regression calculation with equation (11) using the experimental data (Table 1) resulted in k = 0.0062 $m^2\,J^{-1}$ for fecal coliform (R^2 = 0.763, N = 56, P < 0.01). Using this k value, the linear correlation between the calculated and tested survival ratios was statistically significant (R^2 = 0.916, n = 56, P<0.01) (Fig. 4).

MODELING RESULTS AND DISCUSSION

To better understand UV disinfection performance, model simulation was performed for a steady-state recirculating system under variations in daily cycle number, UV power input, and UV_{254} transmittance of the water. Modeling results provide useful information for design and operation of recirculating UV disinfection systems.

The relationship between the relative specific reduction rate (RSRR) and the daily cycle number (Fig. 5) gives a basis for the determination of *daily cycle number for a recirculating UV disinfection system.* The RSRR rises as daily cycle number increases, but the impact of cycle number, when adequately high, is less significant. Therefore, to obtain a

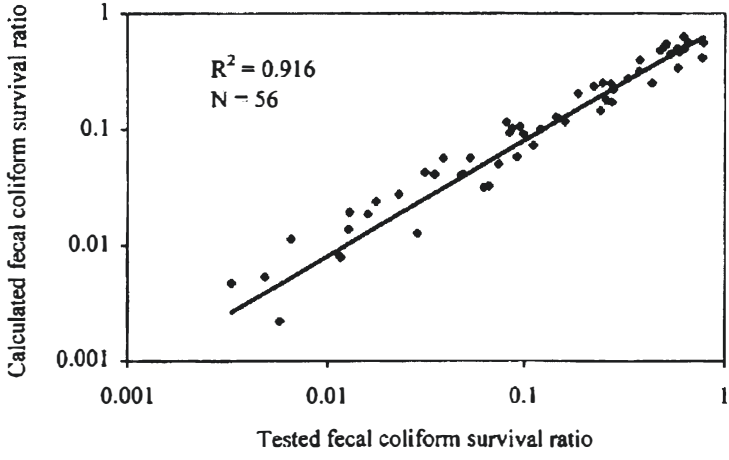
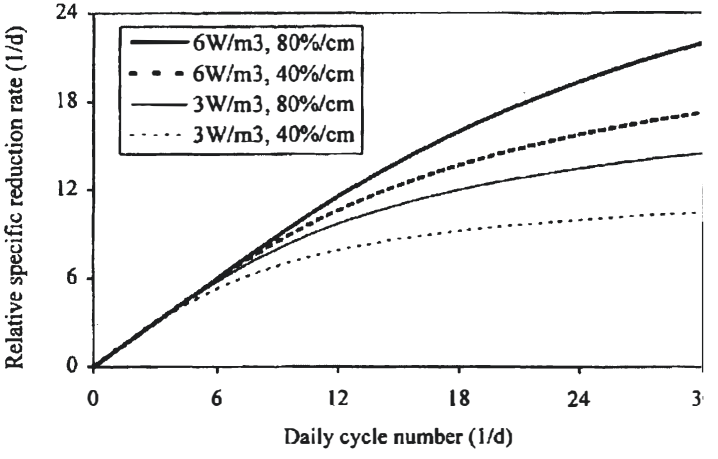


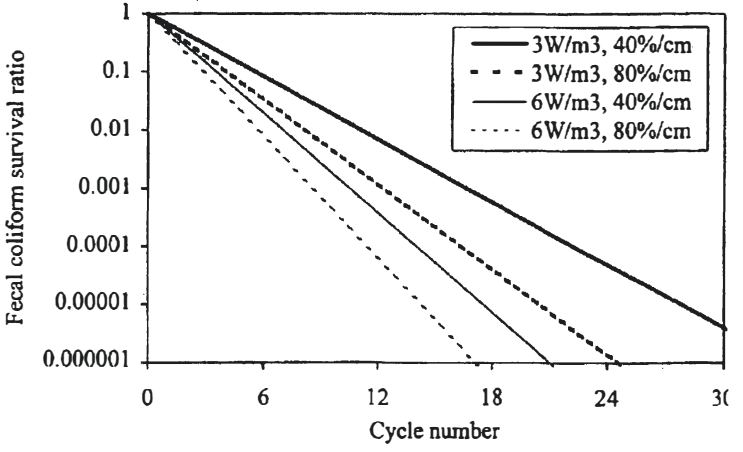
Fig. 4. The linear relationship between calculated and tested fecal coliform survival ratios. R^2 is the determination coefficient of regression, and N is the number of data points.

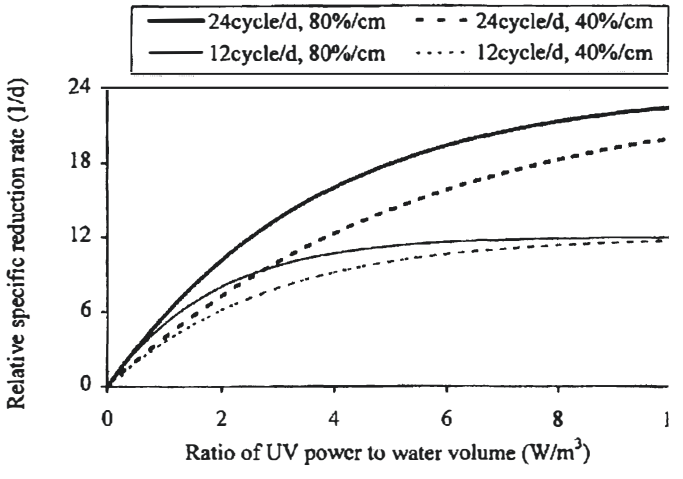
high reduction rate, the number of daily cycles needs to be maintained above a certain level. In recirculating aquaculture systems, the pumping rate is typically determined for a system turnover time of 0.5-1.0 hour (Timmons and Losordo 1994). As indicated in Fig. 5, the daily cycle number required for a high disinfection efficiency is often comparable to that required for nitrification biofiltration purposes.

For a given system without bacterial source production, the FC survival ratio was reduced approximately as an exponential function of the cycle number (Fig. 6). UV power input and water UV transmittance also had significant effects on disinfection efficiency. Given an UV power of 6 W m^{-3}, the cycle numbers required for a survival ratio of 0.00001 were about 17 and 21 for water transmittance values of 80 and 40 % cm^{-1}, respectively. About 24.5 and 33.5 cycles were needed under the same conditions when UV power was 3 W per cubic meter.

Fig. 7 presents information for the determination of UV power per cubic meter of water in a recirculating UV disinfection system. Clearly, a higher power input resulted in a higher reduction rate, but this means more energy consumption. As indicated in equation (8), the maximum RSRR is Q/V, i.e., daily cycle number if time is measured in days instead of seconds. Fig. 7 shows that, when the power input was 6 W m^{-3} and the daily cycle number was 24, RSRR reached 81% and 66% of its maximum value for water with 80 and 40 % cm^{-1} transmittance,


6W/m3, 80%/cm
6W/m3, 40%/cm
3W/m3, 80%/cm
3W/m3, 40%/cm
Relative specific reduction rate (1/d)
Daily cycle number (1/d)
0
6
12
18
24


3W/m3, 40%/cm
3W/m3, 80%/cm
6W/m3, 40%/cm
6W/m3, 80%/cm
Fecal coliform survival ratio
Cycle number
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0
6
12
18
24


24cycle/d, 80%/cm
24cycle/d, 40%/cm
12cycle/d, 80%/cm
12cycle/d, 40%/cm
Relative specific reduction rate (1/d)
Ratio of UV power to water volume (W/m3)
0
6
12
18
24
0
2
4
6
8

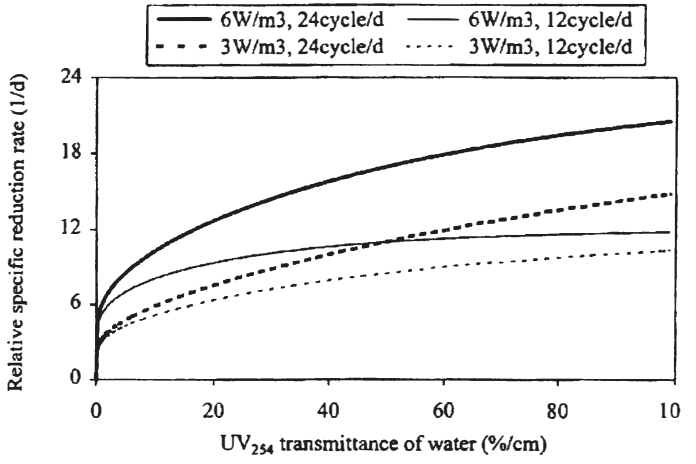
respectively. For a lower daily cycle number, RSRR reached a higher percentage of its maximum. It should be pointed out that the two tested UV units during the experiment were quite new. In reality, the output power of an UV unit depends on its lamp age (U.S. EPA 1986; Darby et al. 1993). For the purpose of UV power design, U.S. EPA (1986) suggested a power efficiency of 0.7 for each UV unit.

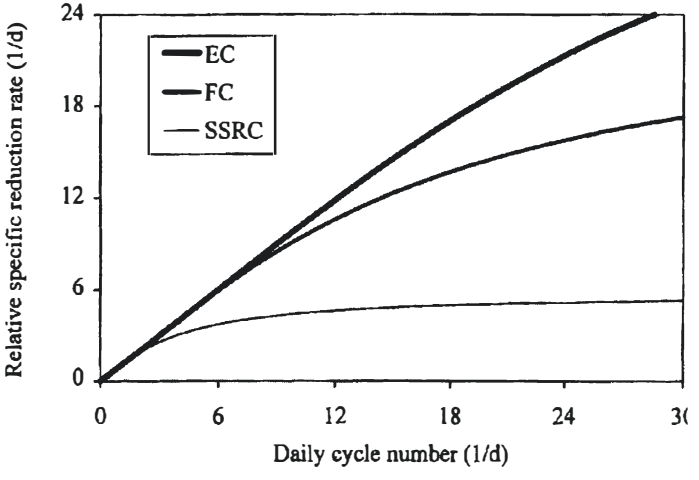
The steady-state relationship between RSRR and water UV_{254} transmittance was plotted in Fig. 8. The reduction rate decreased significantly when the transmittance was less than 20 % cm^{-1}. When the transmittance was above 20 % cm^{-1}, the reduction rate increased slowly with the increase in transmittance, especially for a low daily cycle number. Therefore, it is desirable to maintain the UV_{254} transmittance of the water above 20 % cm^{-1} in order to obtain a satisfactory disinfection efficiency.

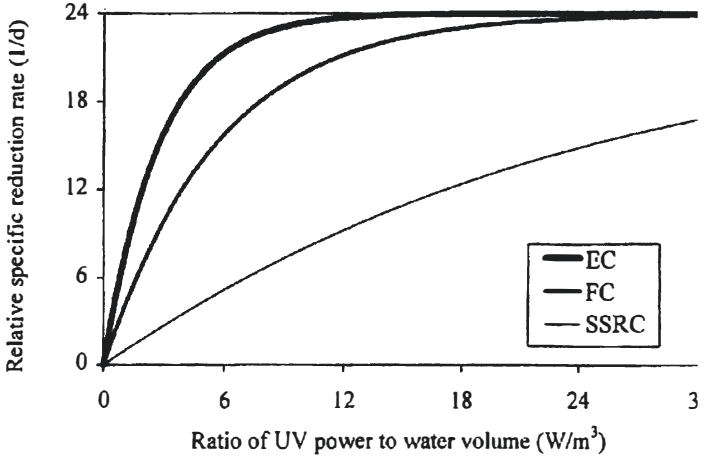
The above modeling results were obtained using the inactivation rate constant of fecal coliform ($k = 0.0062\ m^2\ J^{-1}$). In recirculating aquaculture systems, however, fecal coliform may not be the target for disinfection. Various microorganisms have different survival rates in the UV disinfection process, and thus result in different values of the inactivation rate constant. Table 2 lists some literature values of the parameter for some other microorganism species. Using these k values, respective disinfection effectiveness can be obtained for their species. For the purpose of comparison, Figs. 9 and 10 give the modeling results for two different microorganisms of *Escherichia coli* (EC), spores of sulphite-reducing clostridia (SSRC) by comparison with FC. Clearly, a lower inactivation rate resulted in a lower reduction rate. Fig. 9 indicates that, for the species with a lower inactivation rate, fewer benefits can be obtained through increasing daily cycle number. In this case, UV disinfection efficiency increases more profoundly with increase in UV power input (Fig. 10).

CONCLUSIONS

The experimental results indicated that UV power input, recirculating flow rate and water UV_{254} transmittance were the three most important factors affecting UV disinfection efficiency in a recirculating system.


6W/m3, 24cycle/d
6W/m3, 12cycle/d
3W/m3, 24cycle/d
3W/m3, 12cycle/d
Relative specific reduction rate (1/d)
24
18
12
6
0
0
20
40
60
80
10
UV254 transmittance of water (%/cm)


EC
FC
SSRC
Relative specific reduction rate (1/d)
24
18
12
6
0
0
6
12
18
24
3(
Daily cycle number (1/d)


EC
FC
SSRC
Relative specific reduction rate (1/d)
24
18
12
6
0
0
6
12
18
24
3
Ratio of UV power to water volume (W/m3)

The first-order inactivation rate constant (k) is a key parameter in the UV disinfection model. It was determined in this study as $k = 0.0062\ m^2\ J^{-1}$ for fecal coliform.

Simulation results clearly showed the reduction rate of fecal coliform varied with water cycle rate, UV power input and water UV_{254} transmittance. For disinfecting microorganisms with a lower inactivation rate, the model suggests that increasing UV power input is more effective than increasing daily cycle number.

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