ENHANCEMENT OF WATER DISINFECTION EFFICIENCY USING UV RADIATION WITH THE AID OF A LIQUID-FILM-FORMING DEVICE

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Abstract. This study presents results for the use of UV radiation and a liquid-film-forming device (LFFD) for disinfection of water. Escherichia coli was used as a model microorganism for examining the bactericidal performance of UV. Bacterial inactivation was conducted in a disinfection apparatus with various conditions of UV dosages, air flow rates, and initial bacterial concentrations. Combined UV/LFFD treatments resulted in a greater inactivation efficiency than those for the UV treatment alone. Combined treatment with UV (UV dosage = 3.020×10−20 kJ/m2, initial bacterial concentration = 1.1×105 – 2.2×105 CFU/mL, and room temperature) and LFFD (air flow rate = 2400 L/min) caused 89% inactivation in terms of the bacterial load. In contrast, when the UV treatment alone was used under the same treatment condition, only 29% of the E. coli load was inactivated. These results suggest that the combined UV/LFFD treatments may be useful for water disinfection.

Keywords: bactericidal inactivation, UV radiation, Escherichia coli, water disinfection, liquid-film-forming device.

Classification numbers: 3.4.2, 3.7.4.

1. INTRODUCTION

Practically, improving advanced technologies for water disinfection without producing toxic disinfection by-products (DBPs) has attracted many researchers. Various technologies are used to inactive pathogens in water, for example, chemical disinfection (i.e. chlorine, ozone, etc.) and physical disinfection (i.e. ultraviolet radiation, ultrasonic, heat, high pressure, etc.).

Disinfection using common oxidizers such as chlorine or ozone is the most mature and widespread method owing to its rapid bactericidal effect and low costs. However, chlorine can combine with organic matters in water to produce disinfection byproducts such as trihalomethanes (THMs) and halogenic acetic acids (HAAs) [1]. Also, the ozonation of water
may lead to the formation of bromate in case waters containing bromide such as seawater and brackish water [2].

Compared to chemical disinfection, physical disinfection does not produce DBPs. Thus, heat applications and ultrasound or electric pulse technology can also be used as alternative methods for microorganisms inactivation, but these methods have substantial power requirements and high operational costs [3]. Ultraviolet (UV) disinfection has been considered as an effective method for inhibiting a wide variety of pathogens and does not involve problems relating to the generation of DBPs [4, 5, 6]. However, the disinfection efficiency of UV light is relatively low in waters with high turbidity [3]. Therefore, it would be desirable to develop an innovative water disinfection method in a manner that promotes the benefits of current technology while overcoming the drawbacks of conventional methods.

Currently, liquid-film-forming device (LFFD) was designed to enable produced numerous fine bubbles along with water films, which enhanced the contact area between gas and water and also facilitated oxygen dissolution into water [7]. It is hypothesized that an increase of interfacial contact area between gas and water caused by a LFFD may help increase the transmittance of UV in the water. Bactericidal activity of UV is relatively depended on UV transmittance; therefore, by combining UV and LFFD, the inactivation efficiency may be improved.

Hence, this study examined the use of UV combined with LFFD for water disinfection. The disinfectant activity of the combined UV/LFFD treatment against *Escherichia coli* was conducted under various conditions of UV dosages, air flow rates, and initial bacterial concentrations. The inactivation effects of UV and the combined UV/LFFD were evaluated and compared.

### 2. MATERIALS AND METHODS

#### 2.1. Microorganism preparation

*Escherichia coli* was isolated from domestic wastewater in Hue city, Viet Nam by using the media Coliform agar (Chromocult, Merck) plates. The bacterial inoculum for *E. coli* was prepared by inoculation of bacterial colonies into 100 mL of Luria-Bertani (LB) broth (Wako, Japan). The bacterial culture was incubated for 24 hours at 37 °C with continuous shaking at 150 rpm. The initial enumeration was approximately $10^9$ CFU/mL. The permanent stock was preserved in 20% glycerol and -60°C.

For each disinfection experiment, 100 µL of bacterial glycerol stock was transferred into 100 mL of the broth. The inoculum was incubated at 37°C and shaken at 150 rpm for 24 h.

#### 2.2. Microorganism enumeration

The bacterial colonies were enumerated using the plate count technique. Specifically, a series of ten-fold dilutions were performed by using a sterilized buffer (pH = 7). The cell concentration of *E. coli* was determined by plating 100 µL of either a diluted or undiluted sample onto Coliform agar plates. After incubating the plates for 24 h at 37 °C, the number of colonies was counted on each plate containing 30–300 CFUs and data were reported as CFU mL$^{-1}$. Each sample was analysed in triplicate.

#### 2.3. Preparation of artificial micro-pollution water sample
Tests were performed with artificial micro-pollution water sample. Artificial micro-pollution water sample was prepared by adding 0.02 M solution of sodium thiosulfate pentahydrate (Na$_2$S$_2$O$_3$·5H$_2$O; Wako, Japan) to tap water, which was obtained from the local water supply of Hue city. Whereas, the components of tap water were turbidity (0.1 ÷ 0.2 NTU), pH (7.0 ÷ 7.5), hardness (22 mg CaCO$_3$/L), nitrite (0.003 mg N-NO$_2$/L), residual chlorine (0.5 ÷ 0.6 mg/L), iron (0.01 mg/L), and Mn (0.005 mg/L). Then, residual chlorine in water was quenched completely with a 0.02 M Na$_2$S$_2$O$_3$·5H$_2$O at a ratio of 5 moles of Na$_2$S$_2$O$_3$·5H$_2$O for every 8 moles of NaOCl in the samples. The concentrations of chlorine were determined by the N,N-diethyl-p-phenylenediamine (DPD; Sansyo Co. Ltd., Japan) colorimetric method with an ion-specific meter (H1701, HANNA, Romania) to ensure that no residual chlorine existed in the water.

For all experiments, the prepared bacteria culture was added into the water to obtain desired bacterial concentrations, which represents the initial concentration. Specifically, microbial suspensions of low (0.5 - 1 mL), medium (2 - 3 mL) or high (15 - 75 mL) concentration and 105 L of water were mixed at room temperature to give the desired concentrations (low: 10$^2$ - 10$^3$ CFU/mL, medium: 10$^4$ CFU/mL, and high: 10$^5$ - 10$^6$ CFU/mL, respectively). After this, these mixtures were used as water samples that have been subjected to microbial contamination. The solution was stirred for 15 min to acclimatize the bacteria before starting the experiments. The temperature of the samples was measured with a pH meter (Horiba D-51).

2.4. Apparatus and procedure for UV and UV/LFFD disinfection experiments

The experiment apparatus for disinfection was a clear acrylic chamber with an internal volume of 120 L. The apparatus was designed to include a LFFD (AWA-200, Japan) to create numerous bubbles (Fig. 1). Air was pumped into the device through a LFFD to generate bubbles and to enable vigorous agitation of the influent. Low pressure mercury UV lamps (SCT 20W T8 G13, λ= 254 nm, Lampada, China) were installed above the tank and were about 5 cm far from the water surface. The density of UV-C light was 65 μW/cm$^2$. Before experiment, the UV-C lamps were stabilized by turning them on at least for 15 min.

![Figure 1. Schematic diagram of apparatus used for bacterial inactivation.](image-url)
Disinfection experiments were conducted in batch mode. 105 L sample water, as the influent, was introduced in one shot into the device. The air pump (Ouguan RB-750A) was operated at a flow rate of 50 - 2400 L/min. Then, the UV lamp system and LFFD were turned on. The sensitivity of bacteria to UV or combined UV/LFFD treatments was determined at various conditions of UV dosages, air flow rates, and initial bacterial concentrations, which were applied for 75 min.

The treated water was collected at 0, 15, 30, 45, and 75 min from the six valves of the reactor (Fig.1). During a treatment period of 75 min, the UV intensities were $1.510 \times 10^{18}$, $3.020 \times 10^{18}$, and $4.530 \times 10^{18}$ mJ/cm$^2$ corresponding to the UV dosages of 01, 02 and 03 UV lamps, respectively. Bacterial concentrations were enumerated as mentioned above. All experiments were performed in triplicate.

2.5. Presentation of results

Disinfection efficiency was evaluated by % of the reduction ratio from the number of colonies before and after treatments.

$$\text{Disinfection efficiency (\%) } = 100 \times \frac{(N_0 - N_t)}{N_0}$$

$N_0$ is the number of colonies before treatments and $N_t$ is the number of colonies after treatments.

3. RESULTS AND DISCUSSION

3.1. Effect of air supply rate on E. coli inactivation of the combined UV/LFFD disinfection

The comparison of the bactericidal performance of the UV disinfection and the combined UV/LFFD treatment with different air supply rates (50, 1200 and 2400 L/min) is presented in Fig. 2. Oxygen transfer performance of LFFD in water is showed in Table 1. Overall, disinfection efficiency of the combined UV/LFFD treatments increased with increasing air flow rate. The bactericidal performance of the combined UV/LFFD treatment was higher than that of the UV treatment alone. Specifically, when the initial concentration of E. coli was in the range of $1.1 \times 10^5$ – $2.2 \times 10^5$ CFU/mL, the reduction of the bacterial load was 36 % – 74 % for the former treatment (with the range corresponding to air flow rate from 50 to 2400 L/min, respectively) and 28 % for the latter treatment.

The combined UV/LFFD treatment not only inactivates pathogen but also supplies dissolved oxygen for water. Table 1 shows that with the aid of the LFFD, oxygen dissolved into

![Figure 2. Comparison of bactericidal performance of UV treatment and combined UV/LFFD treatment with different air supply rates (initial bacterial concentration was $1.1 \times 10^5$ – $2.2 \times 10^5$ CFU/mL, room temperature). The error bars represent the standard deviation from the mean.](image-url)
water higher than that in the case of without the LFFD. Also, the higher air flow rate did not bring higher oxygen transfer performance (Table 1). These data are consistent with previous work [8], which found that the increase in gas flow rate led to the notable abatement of the gas absorption into water.

As shown in Fig. 2, when applied the combination of UV and LFFD to inactivate *E. coli*, the higher flow rate promoted higher inactivation efficiency, in terms of the bacterial load. More specifically, when the initial concentration of *E. coli* was in the range of $1.1 \times 10^5 – 2.2 \times 10^5$ CFU/mL, an approximately 36% bacterial reduction was achieved with 50 L/min flow rate, and bacterial inactivation further increased to 65% – 74% with flow rates between 1200 – 2400 L/min during a treatment period of 75 min. These results suggest that higher flow rate resulted in greater *E. coli* inactivation. A plausible explanation for this phenomenon is that the operation at higher flow rate leads to a high ability to produce small bubbles and liquid films, which probably promoted UV penetration into the cells, thereby accelerating *E. coli* inactivation.

*Table 1.* Oxygen transfer performance of liquid thin film apparatus in water.

| Air flow rate (L/min) | Time (min) | DO (mg/L) | Range | Mean ± standard deviation (n = 3) |
|-----------------------|------------|-----------|-------|----------------------------------|
|                       | 0          | 5.1 – 5.4 | 5.3 ± 0.2 |
|                       | 15         | 7.1 – 8.2 | 7.8 ± 0.6 |
| 50                    | 30         | 7.1 – 8.2 | 7.8 ± 0.6 |
|                       | 45         | 7.1 – 8.2 | 7.8 ± 0.6 |
|                       | 60         | 7.3 – 8.2 | 7.8 ± 0.5 |
|                       | 75         | 7.4 – 8.1 | 7.9 ± 0.4 |
| 1200                  | 0          | 6.4 – 6.5 | 6.5 ± 0.1 |
|                       | 15         | 7.8 – 7.9 | 7.8 ± 0.1 |
|                       | 30         | 7.9 – 8.0 | 8.0 ± 0.1 |
|                       | 45         | 8.0 – 8.1 | 8.0 ± 0.0 |
|                       | 60         | 8.1 – 8.1 | 8.1 ± 0.0 |
|                       | 75         | 8.1 – 8.1 | 8.1 ± 0.0 |
| 2400                  | 0          | 6.4 – 6.5 | 6.5 ± 0.1 |
|                       | 15         | 8.0 – 8.0 | 8.0 ± 0.0 |
|                       | 30         | 8.1 – 8.1 | 8.1 ± 0.0 |
|                       | 45         | 8.1 – 8.1 | 8.1 ± 0.0 |
|                       | 60         | 8.2 – 8.2 | 8.2 ± 0.0 |
|                       | 75         | 8.1 – 8.2 | 8.2 ± 0.0 |
3.2. Effect of UV dosage

E. coli inactivation was evaluated at three dosages of UV radiation (1, 2 and 3 UV lamps) and LFFD (50 and 2400 L/min) in both the UV treatment alone and the combined UV/LFFD treatment for 75 min (Fig. 3). In general, the bactericidal activity of both the UV treatment and the combined UV/LFFD treatment increased with increasing UV dosages. The combined UV/LFFD treatment had a greater inactivation efficiency than that of the UV treatment alone.

The bactericidal activity of UV treatment and the combined UV/LFFD treatment significantly increased with increases in the UV dosage. As shown in Fig. 3a, when 01 UV lamp to 03 UV lamps were used, the E. coli load was reduced by 27 % – 32 % within 75 min by UV treatment alone, whereas the inactivation efficiency reached 36 % – 56 % within 75 min by the combined UV (01 to 03 UV lamps)/LFFD (50 L/min) treatment, respectively. Remarkably, the combined UV (01 to 03 UV lamps)/LFFD (2400 L/min) treatment caused 74 % to 95 % inactivation, respectively, in terms of the bacterial load (Fig. 3b). These data indicated that LFFD with a higher UV dosage could be applied to improve the disinfectant activity of UV.

Koivunen et al. [9] observed that disinfection using UV at 14 mJ/cm² resulted in an approximately 94 % reduction of E. coli in peptone water. Beck et al. [10] found that an approximately 99.9 % reduction of E. coli could be achieved with the 254 nm low-pressure UV at a dosage of 11 mJ/cm² (initial bacterial concentration in water was approximately 10⁶ CFU/mL). It is noteworthy that use of the combined UV at 4.53×10⁻¹⁸ mJ/cm² and LFFD (2400 L/min) resulted in an approximately 95 % reduction of E. coli. These findings demonstrate the excellent disinfectant activity of the combined UV/LFFD treatment and suggest that this method could be further developed as a sustainable technology for disinfecting water.

Figure 3. Effect of various UV dosages on E. coli inactivation by (a) UV treatment alone and (b) the combined UV/LFFD treatment. The initial bacterial concentration was 1.4×10⁵ – 3.1×10⁶ CFU/mL. The error bars represent the standard deviation from the mean.

3.3. Inactivation performance of UV/LFFD against E. coli in samples with different initial concentrations

Figure 4 shows the inactivation of E. coli under different initial concentrations at UV (02 lamps)/LTF (2400 L/min). When the initial concentration was low (1.2×10³ – 2.2×10³ CFU/mL), 99 % E. coli was inactivated after 75 min, whereas samples with moderate initial
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concentration \( (1.6 \times 10^4 - 2.3 \times 10^4 \text{ CFU/mL}) \) showed a decrease of 93 % within 75 min. When high initial concentration \( (2.2 \times 10^5 - 3.1 \times 10^5 \text{ CFU/mL}) \) were used, the rate of cell reduction only reached 89 % after 75 min. In general, the bactericidal performance was best at low concentration.

![Figure 4](image)

**Figure 4.** Inactivation performance of the combined 02 UV lamps/LFFD (flow rate 2400 L/min) treatment with different initial concentrations of *E. coli*.

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