Killing rate of colony count by hydrodynamic cavitation due to square multi-orifice plates

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Abstract. Currently,in water supply engineering, the conventional technique of disinfection by chlorination is employed to kill pathogenic microorganisms in raw water. However, chlorine reacts with organic compounds in water and generates disinfection byproducts (DBPs), such as trihalomethanes (THMs), haloacetic acids (HAAs) etc. These byproducts are of carcinogenic, teratogenic and mutagenic effects, which seriously threaten human health. Hydrodynamic cavitation is a novel technique of drinking water disinfection without DBPs. Effects of orifice size, orifice number and orifice layout of multi-orifice plate, cavitation number, cavitation time and orifice velocity on killing pathogenic microorganisms by cavitation were investigated experimentally in a self-developed square multi-orifice plate-type hydrodynamic cavitation device. The experimental results showed that cavitation effects increased with decrease in orifice size and increase in orifice number, cavitation time and orifice velocity. Along with lowering in cavitation number, there was an increase in Reynolds shear stress,thus enhancing the killing rate of pathogenic microorganism in raw water. In addition, the killing rate by staggered orifice layout was greater than that by checkerboard-type orifice layout.

1. Introduction

With the rapid development of economy and society, drinking water sources have been to different extent polluted. There are various pathogenic microorganisms such as bacteria, virus in raw water, which can infect human being and animal diseases, and be water-oborne diseases through effluent of domestic wastewater. In 1894, a bleach technique to kill pathogenic microorganism in raw water was proposed by a German biochemist Traube [1], that is, disinfection by chlorination was used to prevent water-borne diseases, since then it has been being a conventional technique of drinking water disinfection. However, it has been recently found that chlorine reacts with organic compounds in water and generates disinfection byproducts(DBPs),such as trihalomethanes(THMs), haloacetic acids(HAAs) etc. These byproducts are of carcinogenic, teratogenic and mutagenic effects, which seriously threaten human health. In addition, the cost of chlorination is very high and cycle of disinfection treatment is longer. Therefore a novel technique of which is both safe and economic has been expected for drinking water disinfection.

Cavitation and cavitation damage phenomena, which contain formation, growth and collapse of cavitation bubbles as well as physical action and chemical reaction of shock wave and microjet, can be enough to cell disruption of microorganism, breakage coliform colony and inactivation of pathogenic microorganism. Usually, the phenomenon that occurrence of cavitation is based on hydrodynamic principle is called hydrodynamic cavitation. Disruptions of Baker's yeast and Brewer's yeast cells by hydrodynamic cavitation were experimentally investigated by Save, Pandit and Joshi[2, 3], and a comparison with ultrasonic cavitation and mixer were made, only 5%-10% of the energy used by the mixer (blade blender)and the ultrasonic generator horn were used, and an efficient large-scale cell disruption of microorganism can be performed. Agaric, actinomycetes and virus killed by hydrodynamic cavitation due to valve-type device were studied by Bodurova and Angelov[4], their results showed that killing rate of hydrodynamic cavitation can reach 71%~91% within 2-4min, which was related to cavitation number. The effect of cavitation induced by rotary cavitation device on inactivation of Escherichia coli in water was investigated by Tsenter and Khandarkhayeva[5]. The study showed that hydrodynamic cavitation was a simple and perspective technique and could be potentially used for water disinfection. Experimental study of Escherichia coli killed by hydrodynamic cavitation due to the triangular, square and circular multi-orifice plates were carried out by the first author and his co-authors in the self-developed multi-orifice plate-type hydrodynamic cavitation device, effects of orifice size, orifice number, orifice layout, orifice velocity, cavitation number and cavitation time as well as initial concentration of Escherichia coli on killing rate of Escherichia coli were analyzed, and killing mechanism of hydrodynamic cavitation was described[6-8]. In this paper, effects of orifice size, orifice number, orifice layout, orifice velocity, cavitation number and cavitation time on cavitation killing colony count in raw water are experimentally studied.

2. Experimental device and methodology

The experimental study was carried out in the Hydrodynamics Laboratory at Zhejiang University of Technology, the experimental device is shown in Figure 1. The hydrodynamic cavitation working section consists mainly of 5 different types of square multi-orifice plates as shown in Figure 2, and the corresponding geometric parameter is listed in Table 1. The same flow cross-section area was designed for the difFferent multi-orifice plates.

Raw water samples were taken from Shengli river in Hangzhou. Colony counts in raw water ranged between 2.98×10^4 CFU/mL and 4.77×10^4 CFU/mL, the mean value is 3.76×10^4 CFU/mL. Agar plate counting method was used to detect colony count of water sample. Killing rates of colony count in water sample before and after cavitation can be expressed as:

$$\varepsilon = \left(1 - \frac{N_i}{N_0}\right)\times100\% \tag{1}$$

where ε denotes killing rate of colony count; N_0 initial colony count (CFU/mL); N_i colony count at the corresponding cavitation time (CFU/mL).

Figure 1. Sketch of hydrodynamic cavitation setup.

Plate 1Plate 2

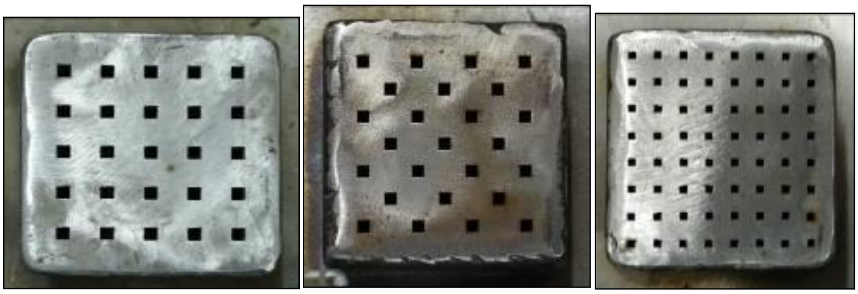

Plate 3Plate 4Plate 5

Figure 2. Square multi-orifice plates.

Table 1. Geometric parameters of square multi-orifice plates.

Plate No.	Orifice number	Orifice side/mm	Orifice layout
Plate 1	9	4.5	Checkerboard-type
Plate 2	16	3.4	Checkerboard-type
Plate 3	25	2.7	Checkerboard-type
Plate 4	25	2.7	Staggered
Plate 5	64	1.7	Checkerboard-type

3. Effect of orifice size on the killing rate

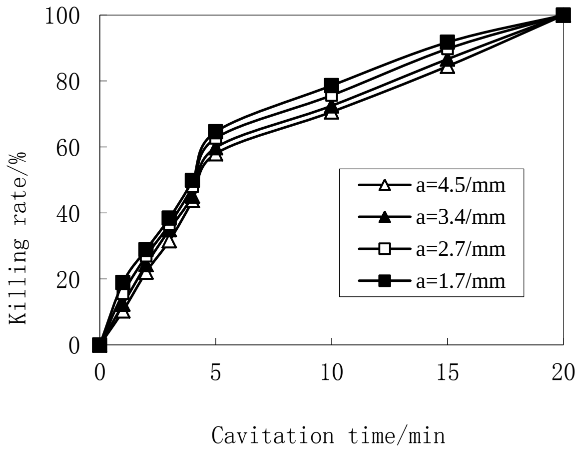

Figure 3. Relation between orifice size and killing rate.

Taking a checkerboard-type multi-orifice plate for example, the square side length a =1.7, 2.7, 3.4 and 4.5mm, to analyze effects of orifice sizes on killing rates of colony count in raw water as shown in Figure 3. It follows from Figure 3 that under the same conditions, killing rate of colony count gradually increases with decrease in orifice side. In the case of the same flow cross-section of multi-orifice, the reduced orifice side shortens jet perimeter, resulting in stronger jet mixing, increase in turbulence intensity, turbulence stress and cavitation effect, so it enhances killing rate of colony count in raw water.

4. Effect of orifice number on the killing rate

Orifice numbers n=9, 16, 25 and 64 were considered to analyze effects of orifice numbers on killing rates of colony count based on checkerboard-type multi-orifice plates as shown in Figure 4. It can be seen that killing rate of colony count increases with increase in orifice number. The reason is that more orifice numbers increases jet numbers, thus intensifying multi-jet entrainment and hydraulic shear, then the killing rate increases.

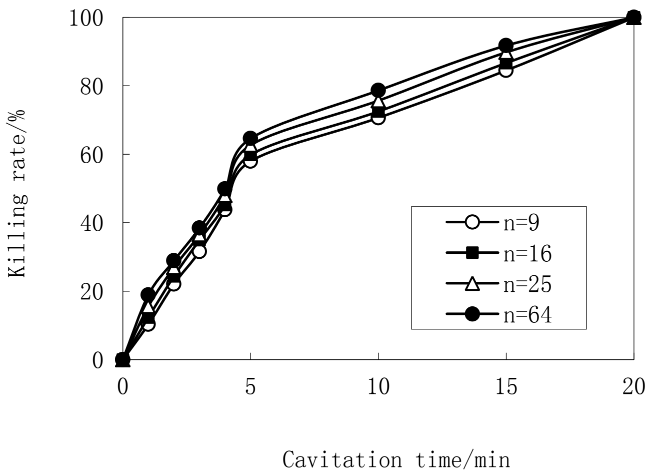

Figure 4. Relation between orifice number and killing rate.

5. Effect of orifice layout on the killing rate

A comparison between 25-orifice checkerboard-type layout and 25-orifice staggered layout was made to study effects of orifice layouts on killing rates of colony count as shown in Figure 5. We can see from Figure 5 that data points of the killing rates between checkerboard-type and staggered layouts are almost overlapped, in which the staggered killing rate is slightly greater than that of the checkerboard-type. The reason is that the staggered layout slightly increased the multi-jet mixing and shear stress, so the killing rate slightly increases.

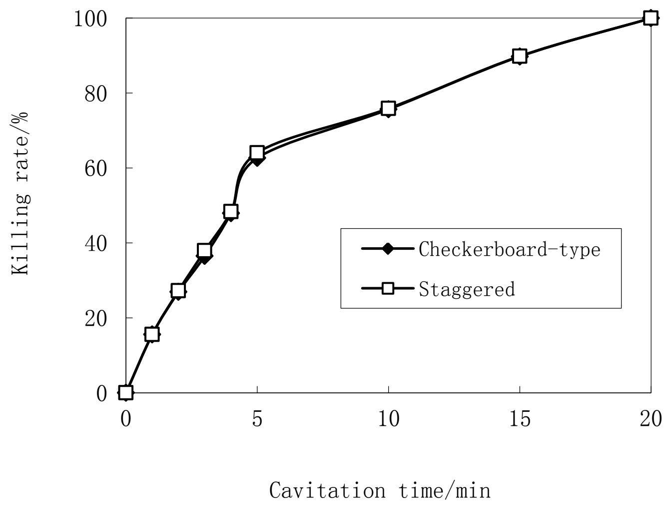

Figure 5. Relation between orifice layout and killing rate.

6. Effect of cavitation number on the killing rate

Cavitation level can be described by cavitation number as follows:

$$\sigma = \frac{p_0 - p_\upsilon}{\rho V_0^2 / 2} \tag{2}$$

where p_0 denotes absolute pressure; p_υ saturated vapor pressure; V_0 orifice velocity; ρ water density.

Factors affecting flow cavitation are related to absolute pressure p_0, saturated vapor pressure p_v, viscosity μ, orifice velocity V_0, orifice size a, water density ρ and flow cross-section of multi-orifice A, and can be written as:

$$f(p_0, p_{\mathrm{v}}, \mu, V_0, a, \rho, A) = 0 \tag{3}$$

Considering the expression of cavitation number, and after dimensional analysis, we have:

$$\frac{\Delta p}{\rho V_0^2/2} = f_2\left(\frac{\mu}{\rho V_0 a}, \frac{A}{a^2}\right), \quad \frac{\mu}{\rho V_0 a} = \frac{1}{R_e}, \quad \frac{\Delta p}{\rho V_0^2/2} = \sigma, \quad \frac{A}{a^2} = n \tag{4}$$

Then we can obtain:

$$\sigma = f_3(R_e, n) \tag{5}$$

When orifice number n=const, cavitation number σ is only function of Reynolds number Re, that is:

$$\sigma = f_4(R_e) \tag{6}$$

Taking into account $\sigma \propto 1/V_0^2$, $\mathrm{Re} = \propto V_0$, so cavitaiton number decreases with increase in Reynolds number.

Relation between killing rate and cavitation number is listed in Table 2. With decrease in cavitation, increase in Reynolds number and Reynolds stress, then killing rate of colony count increases.

Table 2. Variation of killing rate with cavitation number.

Plate No.	Checkerboard -type 9-orifice	Checkerboard -type 16-orifice	Checkerboard -type 25-orifice	Staggered25-orifice	Checkerboard -type 64-orifice
σ	0.254	0.247	0.244	0.225	0.193
ε (%)	99.93	99.96	99.97	99.98	99.98

7. Effect of orifice velocity on the killing rate

Relation between orifice velocity and killing rate is shown in Figure 6. It can be easily seen that the higher the orifice velocity, the greater the killing rate. With increase in orifice velocity, cavitation number further lowers, more cavitation bubbles occur, and that cavitation cycle increase, therefore the killing rate of colony count rises.

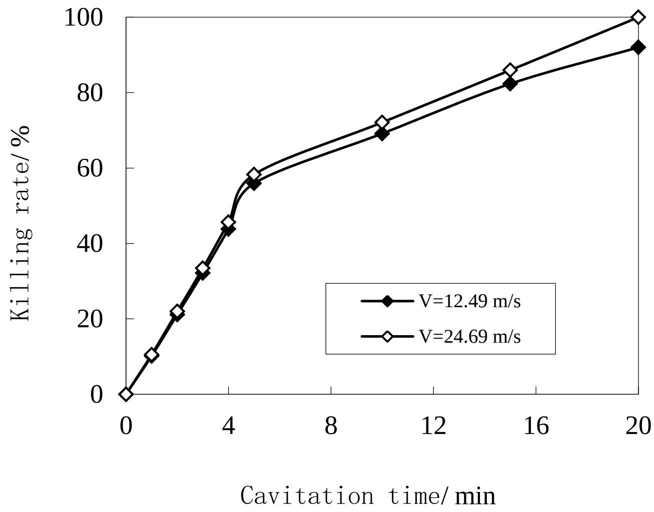

Figure 6. Relation of orifice velocity and killing rate.

8. Conclusions

Through the experimental study of killing rate of colony count in raw water, we can draw some conclusions as follows:

(1) The reduced orifice can enhance killing rate of colony count;

(2) The increased orifice number can enhance killing rate of colony count;

(3) The difference of killing rates between checkerboard-type and staggered layouts is smaller in the case of the experimental conditions, however, the killing rate of staggered layout is slightly greater than that of checkerboard-type layout;

(4) The orifice velocity can enhance killing rate of colony count;

(5) The lowering cavitation number can enhance killing rate of colony count;

(6) The prolonging cavitation time can enhance killing rate of colony count.

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