Experimental Study of Pathogenic Microorganisms Inactivated by Venturi-Type Hydrodynamic Cavitation with Different Throat Lengths

Zhiyong Dong
College of Civil Engineering and Architecture at Zhejiang University of Technology, Hangzhou, CHINA
dongzy@zjut.edu.cn

Zhaoyu Qin
College of Civil Engineering and Architecture at Zhejiang University of Technology, Hangzhou, CHINA
136148788@qq.com

ABSTRACT

Based on self-developed Venturi-type hydrodynamic cavitation device with different throat length-radius ratios *L/R* in Hydraulics Laboratory at Zhejiang University of Technology in China, 4 throat length-radius ratios *L/R*=10, 30, 60 and 100, and 4 raw water percentages V_0/V=25%, 50%, 75%, and 100% were considered, Escherichia coli and total colony count were selected for indicator bacteria, effects of throat length-radius ratio, throat velocity, cavitation time, raw water percentage and cavitation number on inactivating pathogenic microorganism in raw water by hydrodynamic cavitation were experimentally studied. The results showed cavitation damage of cells of pathogenic microorganisms occurred by microjets and shock waves due to cavitation bubble collapse. The lower the flow cavitation number, the higher the killing rate of E. coli and total colony count. When flow velocity was lower or raw water percentage was higher, killing rate gradually increased with increase in throat length-radius ratio; when flow velocity was higher or raw water percentage was lower, killing rate was almost independent of throat length-radius ratio. Inactivated effect of pathogenic microorganisms can be further enhanced by increasing throat velocity or prolonging cavitation time. Hydrodynamic cavitation is a novel disinfection technique for drinking water without disinfection byproducts (DBPs) and no need to add disinfectant.

Keywords: hydrodynamic cavitation, throat length, raw water percentage, pathogenic microorganism, killing rate

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, viruses and parasites, which can infect human being and animal diseases, and be water-borne diseases through effluent of domestic wastewater. In 1894, a bleach technique to kill pathogenic microorganisms in raw water was proposed by a German biochemist Traube (1894), 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 raw 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 (Doyle, 1997; Simpson & Hayes, 1998).In addition, the cost of chlorination is very high and the 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 waves and microjets, can be enough to disrupt cell of microorganism, break coliform colony and kill 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, et al.(1994) and Save, et al.(1997), 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 consumed, and an efficient large-scale cell disruption of microorganism can be performed. Agaric, actinomycetes and virus killed by hydrodynamic cavitation due to the valve-type device were studied by Bodurova & Angelov(2004), 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 & Khandarkhayeva (2012). 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 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 on killing rate of E. coli were analyzed, and killing mechanism of hydrodynamic cavitation was described (Chen, et al., 2016; Liu, et al., 2016; Zhang, et al., 2016). This paper aims at experimentally studying effects of throat length-radius ratio, throat cavitation number, throat velocity, cavitation time, and raw water percentage on killing pathogenic microorganisms by hydrodynamic cavitation based on the self-developed Venturi-type hydrodynamic cavitation device with different throat length-radius ratios.

2 EXPERIMENTAL FACILITY AND METHODOLOGY

An experimental study was carried out in a self-developed Venturi-type hydrodynamic cavitation device with different throat length-radius ratios in the Hydraulics Laboratory at the Zhejiang University of Technology in China as shown in Figure 1.

Figure 1. Venturi-type hydrodynamic cavitation setup.

The experimental setup was a looped system, which consisted mainly of hydraulic pumps, inner and outer tanks, Venturi working section, rotor flowmeter, pressure gauges, and pipeline. Venturi working section mainly contained contraction, throat and diffusion sections. 4 types of throat length-radius ratios L/R=10, 30, 60 and 100were designed in the experiment, in which L and R denote throat length, hydraulic radius of throat, respectively, the corresponding Venturi combinations of 300-50-300 (contraction length-throat length-diffusion length, the unit is mm), 300-150-300, 300-300-300 and 300-500-300 as shown in Figure 2.

(a) Venturi combination 300-50-300

(b) Venturi combination 300-150-300

(c) Venturi combination 300-300-300

(d) Venturi combination 300-500-300

Figure 2. Venturi combinations of different throat length-radius ratios.

Diffusion angle in diffusion section was 2.9, and cross-sectional area in throat 20×20mm^2, the detailed geometric parameters are listed in Table 1. The pipeline system was divided into main pipeline and branch pipeline. The main pipeline was used to generate hydrodynamic cavitation, and the branch pipeline to regulate the flow rate. The flowrate was measured with rotor flowmeter LZB-100. The pressure in the cavitation working section was real-timely acquired by the pressure data acquisition system Sino Cera YE6263. The raw water samples were taken from a non-potable water source Shengli Riverin Hangzhou city. The initial concentration of total colony count $C_c = 5.82 \times 10^5 - 7.95 \times 10^5 \mathrm{CFU/m}$, and the initial concentration of Escherichia coliform, $C_E = 0.36 \times 10^4 - 1.85 \times 10^4 \mathrm{CFU/mL}$ which were diluted by a certain proportion of tap water. Raw water percentageV_0/V = 25, 50, 75, 100%, where V_0denotes raw water volume of the test sample, the total volume of the test sample. The test sample containing pathogenic microorganisms was poured into the inner tank of hydrodynamic cavitation device and then flowed through the Venturi-type working section. Effects of throat length-radius ratio L/R, throat cavitation number, cavitation time, raw water percentage on killing pathogenic microorganisms by hydrodynamic cavitation were experimentally studied. Sampling time were respectively 0, 1, 2, 3, 4, 5, 10, 15 and 20min before

and after cavitation. E. coli and total colony count were referred to as indicator bacteria of pathogenic microorganisms. Pathogenic microorganism count in raw water was detected by agar plate counting. Throat velocity U_1=25.2 m/s for the case of one pump operation, and the velocityU_2 =30 m/s for two pumps. Killing rates of E. coli K_E and total colony count K_C can be respectively defined as follows:

$$K_E = \frac{C_E - C_t}{C_E} \times 100\% \quad (1)$$

$$K_C = \frac{C_C - C_t}{C_C} \times 100\% \quad (2)$$

where C_E denotes the initial concentration of E. coli; C_C initial concentration of total colony count; C_t the corresponding concentration at cavitation time *t*.

Table 1. Geometric parameters of Venturi-type working section

Throat length *L*(mm)	Hydraulic radius of throat *R* (mm)	Diffusion length(mm)	Throat length-radius ratio *L/R*
50	5	300	10
150	5	300	30
300	5	300	60
500	5	300	100

3 EFFECT OF THROAT LENGTH-RADIUS RATIO ON CAVITATION NUMBER

Hydrodynamic cavitation intensity can be described by cavitation number σ as follows:

$$\sigma = \frac{p - p_v}{\rho U^2/2} \quad (3)$$

where p denotes absolute pressure; p_v the saturated vapor pressure of water; ρ water density; σ throat velocity.

As we know, water flow in Venturi contraction section exhibits an increase in velocity and decrease in pressure. A sit enters into throat section, its pressure drops to negative pressure to generate cavitation bubbles, and the cavitation flow entering into diffusion section decreases in velocity and increases in pressure to result in the occurrence of bubble collapse, thus generating microjets and shock waves. For the case of diffusion angle$\alpha = 2.9^o$, the effect of throat length-radius *L/R* on cavitation numberσin the throat is shown in Figure 3.

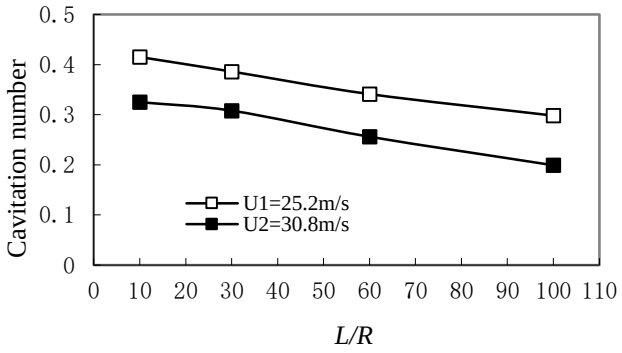


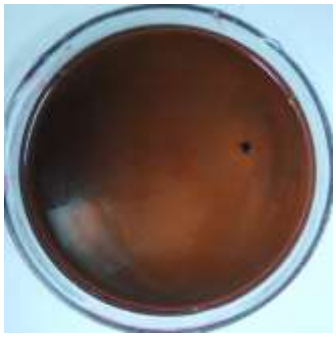
Figure 3. Effect of throat length-radius ratio on cavitation number.

It follows from the Figure that for the different throat length-radius ratios *L/R*, throat cavitation number σ in the case of two pumps (U_2 =30 m/s) is obviously lower than that in the case of one pump (U_1=25.2 m/s), and variation of the cavitation number σ with the length-radius ratio *L/R* almost exhibits linear decrease for the different velocities.

4 EFFECT OF THROAT LENGTH-RADIUS RATIO ON KILLING RATE OF E. COLI

For the case of Venturi combination 300-300-300, throat length-radius ratio *L/R*=60, and raw water percentageV_0/V = 100%, photographs of agar plate for E. coli colonies are shown in Figure 4. E. coli colonies $C_E = 1.78 \times 10^4\ CFU/mL$before cavitation (*t*=0min) in the water sample, after cavitation time 15min, the E. coli colonies reduced to 50 *CFU*/mL, the killing rate reached 99.99%. Microjets and shock waves due to bubbles collapse could force cells of pathogenic microorganisms to generate cavitation damage. The role of each bubble should be equivalent to a microreactor, bubble close to pathogenic microorganism could generate asymmetric collapse as a result of microjet, which would be of "electric drill" effect. Also, turbulence and shear stress play the important role in the disruption of pathogenic microorganisms.

(a) t =0min,$C_E = 1.78 \times 10^4$CFU/mL



(b) t=15 min, C_E = 50 CFU/mL

Figure 4. Photographs of agar plate for E. coli colonies before and after cavitation (L/R=60,V_0/V=100%).

When raw water percentageV_0/V=50% and hydrodynamic cavitation time t=15min, the effect of throat length-radius ratio L/R on killing rate of E. coli is shown in Figure 5. As can be seen in the Figure, for L/R=10, 30, 60 and 100, killing rates at U_2=30.8m/s were 100%, and killing rates at U_1 =25.2m/s gradually increases with an increase in L/R. Obviously, killing rates at higher velocity was considerably higher than that at lower velocity. The reason is that cavitation number is inversely proportional to flow velocity, that is, the higher the velocity, the lower the cavitation number, and more cavitation bubbles generate, so it can be able to enhance the killing rate of E. coli.

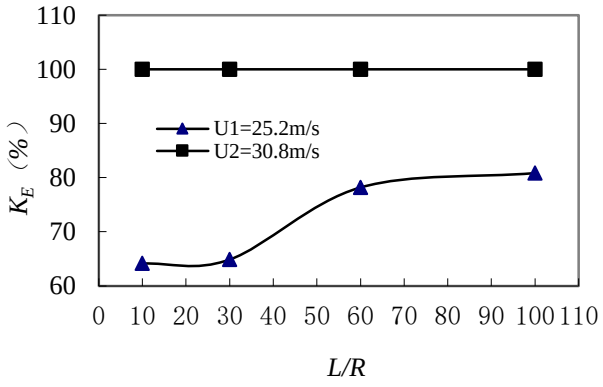


Figure 5. Variation of E. coli killing rate $K_E$with throat length-radius ratio L/R at different velocities.

Table 2. Effect of throat length-radius ratio L/R on killing rate of E. coli K_E.

V_0/V	L/R			
	10	30	60	100
25%	100%	100%	100%	100%
50%	100%	100%	100%	100%
75%	98.13%	98.97%	99.20%	100%
100%	94.84%	95.56%	96.50%	100%

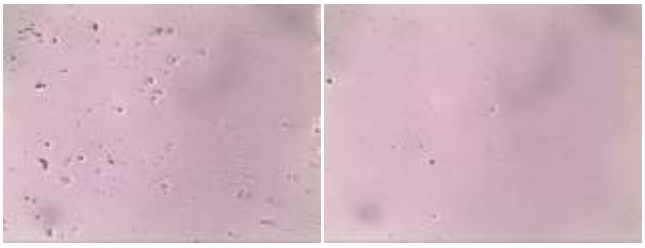
In the case of U_2 =30.8m/s, cavitation time t=15min andV_0/V =25%,50%, 75% and 100%,theeffect of throat length-radius ratio L/R on killing rate of E. coli K_E is listed in Table 2. We can see from the Table that when V_0/V=25% and 50%, killing rates $K_E$at different L/R are 100%; when V_0/V=75% and 100%, the killing rates gradually increase with increase in L/R, the K_E is more than 90%, and that the killing rate at V_0/V=75% is higher than that at V_0/V=100%. When L/R=100, killing rates at different raw water percentages can reach 100%. Because raw water samples were taken from a non-potable water source, the concentration of E. coli colonies was high up to 1.78×10^4CFU/mL, which was far higher than microorganism index of standards for drinking water quality issued by China Environmental Quality Standard for Surface Water (GB3838-2002), it could be still able to completely kill E. coli colonies in raw water through slightly prolonging hydrodynamic cavitation time.

5 EFFECT OF THROAT LENGTH-RADIUS RATIO ON KILLING RATE OF TOTAL COLONY COUNT

Taking a microscopic detection of total colony count in the case of Venturi combination 300-300-300, throat length-radius ratio L/R=60, raw water percentageV_0/V=100% and throat velocityU_2 =30.8m/s for example, theinitial concentration of total colony count in a water sample $C_c - 6.51 \times 10^5$ CFU/mL, after hydrodynamic cavitation time t=20min, killing rate of total colony count could reach 98.82% as shown in Figure 6. WhenV_0/V =50% and hydrodynamic cavitation time t=15min, at throat velocitiesU_1 = 25.2 m/s andU_2=30.8m/s, the effect of throat length-radius ratio L/R on killing rate of total colony count $K_C$is shown in Figure 7. It follows that the killing rate K_C gradually increases with increase in the L/R, and the higher the velocity, the greater the killing rate.

For raw water percentages V_0/V=25%, 50%, 75% and 100%, when throat velocity U_2=30.8m/s and hydrodynamic cavitation time t=15min, a relation between throat length-radius ratio L/R and killing rate of total colony count K_C is listed in Table 3. It could be seen that when theV_0/V is lower, the killing rates at different L/R can reach 100%; when the V_0/V is higher,

the killing rates tend to be 100% with an increase in *L/R*. When throat length-radius ratio was longer, e.g., *L/R*=60 and 100, the killing rate K_C was independent of raw water percentagesV_0/V, which could completely kill total colony count; when the *L/R* was shorter, the killing rate gradually decreased with increase in theV_0/V.



t = 0 min t = 20 min

Figure 6. Photographs of microscopic detection for total colony count (*L/R*=60 andV_0/V=100%).

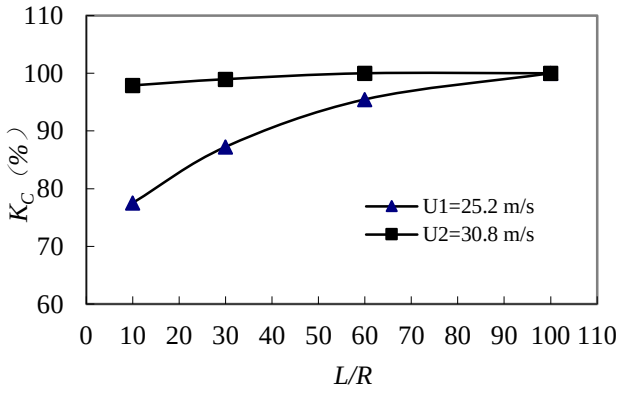


Figure 7. Variation of killing rate of total colony count K_C with throat length-radius ratio *L/R* at different velocities.

Table 3. Effect of the *L/R* on killing rate of total colony count K_C

V_0/V	*L/R*			
	10	30	60	100
25%	100%	100%	100%	100%
50%	97.89%	98.97%	100%	100%
75%	96.88%	97.14%	100%	100%
100%	88.88%	95.62%	99.18%	100%

6 CONCLUSIONS

Through the experimental study of killing E. coli and total colony count by Venturi-type hydrodynamic cavitation at different throat length-radius ratios, we can draw some conclusions as follows:

a) Cavitation number in the Venturi throat almost exhibited a linear decrease with increase in throat length-radius ratio. The lower the cavitation number, the greater the killing rate to E. coli and total colony count.
b) When velocity was lower or raw water percentage higher, the killing rate of hydrodynamic cavitation to E. coli gradually increased with increase in the throat length-radius ratios; when velocity was higher or raw water lower, the killing rate was independent of throat length-radius ratios.
c) When raw water percentage was lower, the killing rates at different throat length-radius ratios could reach 100%; when raw water percentage was higher, the killing rates gradually tended to be 100% with anincrease in the length-radius ratios. If the length-radius ratio was longer, the killing rate was independent of raw water percentage and could completely kill total colony count; if the length-radius ratio was shorter, the killing rates gradually decreased with increase in raw water percentages.
d) The killing rates of E. coli and total colony count increased with prolonging in hydrodynamic cavitation time. Because a variety of pathogenic microorganisms existed in raw water, hydrodynamic cavitation time to kill total colony count lasted longer than that to kill E. coli.

7 ACKNOWLEDGMENT

The authors would like to acknowledge the support of the National Natural Science Foundation of China (Grant No.51479177) for this study.

REFERENCES

Bodurova, D. & Angelov, M., 2004. Intensification the process of water purification by hydrodynamic cavitation. Production and Industrial Engineering Association Scientific Conference with International Participation, Manufacturing and Management in 21st Century. Ohrid, the Republic of Macedonia, University “Ss Cyril and Methodius” – Skopje Faculty of Mechanical Engineering.

Chen, L., Dong, Z. & Lui, C., 2016. Experimental study on disinfection of Escherichia coli by hydrodynamic cavitation behind square multi-orifice plates. Journal of Hydroelectric Engineering, 35(9), pp. 48-54.

Doyle, T. J., 1997. The association of drinking water source and chlorination by-products with cancer incidence among postmenopausal women in Iowa. American Journal of Public Health, 87(7), pp. 1168-1176.

Liu, C., Dong, Z. & Chen, L., 2016. Experimental study of Escherichia coli killed by hydrodynamic cavitation due to circular multi-orifice plates. China Environmental Science, 36(8), pp. 2364-2370.

Save, S. S., Pandit, A. B. & Joshi, J. B., 1994. Microbial cell disruption : role of cavitation. The Chemical Engineering Journal, Volume 55, pp. 67-72.

Save, S. S., Pandit, A. B. & Joshi, J. B., 1997. Use of hydrodynamic cavitation for large-scale cell disruption. Chemical Engineering Research and Design, 75(C1), pp. 41-49.

Simpson, K. L. & Hayes, K. P., 1998. Drinking water disinfection by-products: an Australian perspective. Water Research, 32(5), pp. 1522-1528.

Traube, M., 1894. Leben und Wirken des universellen Privatgelehrten und Wegbereiters der physiologischen Chemie. Med. Dissertation., Signatur 94 HB 1449: Universitätsbibliothek der Humboldt Universität Berlin.

Tsenter, I. & Khandarkhayeva, M., 2012. Effect of hydrodynamic cavitation on microbial inactivation: Potential for disinfection technique, July, Lviv, Ukraine: The 13th Meeting of the European Society of Sonochemistry.

Zhang, X., Dong, Z. & Chen, L., 2016. Experimental study on Escherichia coli killed by hydrodynamic cavitation behind triangular multi-orifice plates. Journal of Hydroelectric Engineering, 35(8), pp. 65-71.