Regular Paper

Sterilization Action on Cavitation Phenomenon Generated by Magnetostrictive Actuator

Sotoshi YAMADA*1, Shotarou NAKAMURA*2, Makiko KAKIKAWA*1 and Toshiyuki UENO*1

Giant magnetostrictive actuator has potential for producing a huge stress and minute stroke unlike electromagnetic actuators using electromagnetic force. We proposed the powerful generation of cavitation in water medium driven by the actuator. The collapse of cavitation generates pulse shock wave and also brings about radicals generating by addition of titanium oxide. The previous researches show the generation of cavitation and radicals based on the methylene blue test method, and the destructive influence of both virus and bacteria was recognized. The paper proposes a new apparatus of a circulation type system to aim the large capacity, and discusses the evaluation of sterilization and inactivation quantitatively. And we observed the biological condition of the cell to check the biological effect after sterilization.

Keywords: giant magnetostriction, actuator, cavitation, pulse power, radical, sterilization. bacteria, virus.
(Received: 31 May 2012, Revised: 5 June 2013)

1. Introduction

When the titanium dioxide (TiO_2) as a photocatalyst material is added in a water medium and also an irradiation of light or ultrasonic wave is applied, it is well-known that TiO_2 excited by the irradiation generates radicals used for water purification, sterilization, washing, and etc. [1,2]. In radical generation by an ultrasonic wave, micro air bubbles are made by the longitudinal wave of an ultrasonic into a water medium. TiO_2 excites with the energy of about 1 GPa, or 10,000 K, that occurs at the collapse of air bubbles and the radicals occur [3]. On the contrary, it is possible to generate cavitation inside of the tank containing a water medium by decompressing to vacuum [4,5]. In order to change the inside of a tank into a vacuum state, the stress more than the product of atmospheric pressure and a cross-sectional area is required. A giant magnetostrictive actuator compared with an electromagnetic one can generates a huge stress, and has a simple structure. The actuator can serves as a direct driver to the adiabatic expansion of space containing water. Moreover, this equipment can generate cavitation to the whole medium since the whole inside of a tank is decompressed uniformly.

The previous research clarified that the cavitation and radicals generating by this equipment were detected by the verification experiment using a methylene blue reagent, and both virus and bacteria could be inactivated and sterilized [4-6]. Especially both the pressure shock wave of a cavitation and a radical reaction give the effective inactivation to virus. We observed that the membrane (coat protein) was destroyed, and RNA flowed out [6]. On the other hand, bacterium is ten times as bigger cell as virus, and self-multiplication is possible. Moreover, the cell membrane has strong structure as a lipid bilayer membrane, Therefore, we proofed the sterilization by using *E. coli* as bacteria.

In the paper, we proposed the continuous mechanism processing water medium at a bathtub. This equipment enables us to evaluate the effective inactivation and sterilization. Moreover, it was verified by an electrophoresis apparatus whether the radical action give the change of cell structure.

2. Circulating Type Cavitation Generation and Methodology

2.1 Sterilization by Cavitation Generating Equipment

From the previous works, the sterilization mechanism of the virus and bacteria by cavitation and radical is summarized in Fig. 1 [6]. At the state of the adiabatic expansion, the inside of a tank filled by water medium is made into a vacuum by the piston connected directly the giant magnetostrictive actuator, and cavitation bubble occurs in a water medium. When cavitation air bubbles collapse, a pulse shock wave is generated and give a physical damage to virus and bacteria. Moreover, the collapse pulse power excites titanium dioxide (band gap energy, 3.2 eV) like photocatalyst and radicals with high oxidization decomposition power generate. The radicals attack virus and bacteria by chemical effects. In the mechanism, both physical stress and chemical reaction act as sterilization and inactivation to bacteria and virus.

2.2 Cavitation Generator with Circulation Mechanism of Water Medium

The outline of cavitation generator with the circulation system is shown in Fig. 2 and the parameters are listed in Table 1. The equipment has the composition that the circulated equipment was connected to the external tank and the pump for

Correspondence: S. YAMADA, Institute of Nature and Environmental Technology, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan
e-mail:yamada@magstar.ec.t.kanazawa-u.ac.jp
*1Kanazawa University
*2Nakamura-tome Precision Industry co.itd.

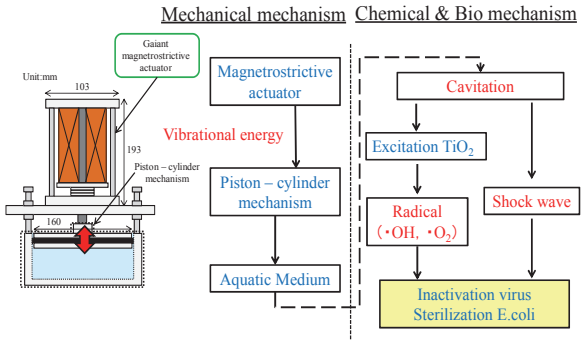

Fig. 1. Sterilization phenomenon based on cavitation generator.

circulating the liquid. When the pump is under a stop, the inside of an equipment tank will be in a sealing state by a check valve connected to the cylinder. In according to the maximum thrust of a giant magnetostrictive actuator, a decompression ability of the piston with 4.2 × 10^5 Pa can fully decompress to a vacuum, then radicals will be generated. When the pump is in operation, the whole liquid for purification is agitated. It is possible to agitate and process the liquid for purification by repeating a stop and drive of this pump.

2.3 Evaluation of Sterilization by Cavitation Generator

2.3.1 Quantitative Evaluation of Sterilization for Batch Processing

When the number of cell by using non-cyclical cavitation generating equipment decreases by a constant decrease factor λ_d like biological phenomena, the existence of cell $N(t)$ is expressed by,

$$dN(t)/dt = -\lambda_d N(t) \quad (1)$$

$$N(t) = N_0 \exp(-\lambda_d t) \quad (2)$$

where N_0 is the initial number of cell.

Fig. 3 shows the results of *E.coli* bacteria sterilization by the continuous drive of cavitation generator. The horizontal axis is the number of vibration x expressed by,

$$x = 2ft \quad (3)$$

where f is the frequency of exciting current. The viable ratio which set the cell count of initial bacteria to one was drawn in Fig. 3. The experimental result denotes that the ratio of *E.coli* is decreasing exponentially expressed by Eq. (2).

2.3.2 Quantitative Evaluation of Sterilization for Circulation Mechanism

We derive the existence expression of a cell $N(t)$ for the cavitation generator with the circulation mechanism as shown in Fig. 2. When the ratio of cylinder volume to the total water is α (< 1.0), and it is assumed that bacteria is distributed uniformly, the breeding ratio of a bacteria $dN(t)/dt$, is expressed by,

$$dN(t)/dt = \{-\alpha\lambda_d + (1-\alpha)\lambda_i\} N(t) \quad (4)$$

where λ_i is a breeding factor. As virus cannot be increased by oneself, λ_i is null for virus. The solution to Eq. (4) is expressed by,

$$N(t) = N_0 \exp\{-\alpha\lambda_d + (1-\alpha)\lambda_i\} \quad (5)$$

If the following condition,

$$\alpha\lambda_d > (1-\alpha)\lambda_i \quad (6)$$

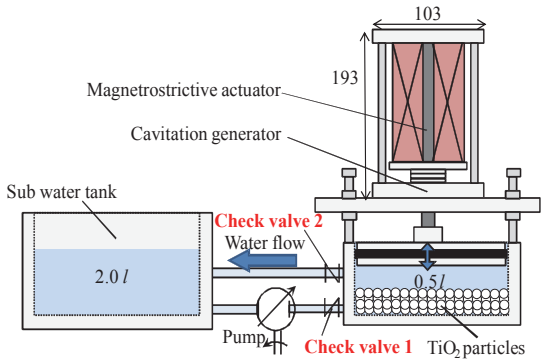

Fig. 2. Cavitation generator connected by water circulation mechanism.

Table 1　Parameters of cavitation generator

Parameters	Value
Actuator diameter	103 mm
Actuator height	192.9 mm
Plunger material	Terfenol-D
Size of plunger	20 mmϕ ×120 mm
Magneto motive force	6,000 AT
Maximum stroke	120 μm
Maximum force	8,300 N (830 kgf)
Inner diameter of cylinder	160 mm$^{\phi}$
Capacity of water tank	500 m l
Capacity of external tank	2000 m l
Decompression ability	4.23 ×10^5 Pa

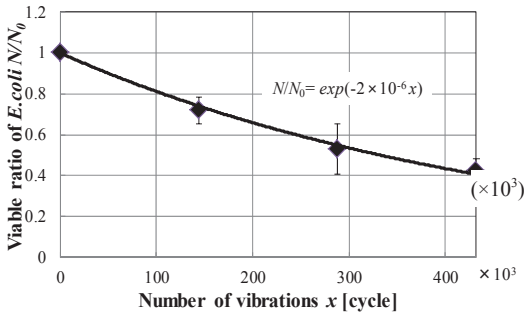

Fig. 3. Experimental results of *E. coli* bacteria sterilization for batch processing.

is satisfied, the ratio $N(t)/N_0$ is decreasing exponentially on the cavitation equipment with the circulation mechanism. However, since the liquid for purification was not always under exposure of a cavitation, we verified whether the decrease of bacteria and virus follows Eq. (6) by the sterilization experiment using *E.coli* and virus.

2.4 Inactivation of Virus by Circulation Type Equipment

The cavitation generating equipment was driven circulating the liquid for purification, and the inactivation of a virus was evaluated experimentally. The phage with a simple structure, *MS2*, was used as a virus. The volume of water is 2.5 *l*, and TiO_2 of 2 mm^{ϕ} is filled up with 500 g into the cylinder. The condition of an actuator is with exciting current of 2.5 A, the vibration frequency is 240 Hz, and the driving time is 180 min. After the whole solution by the flow velocity 2.5 *l*/min and the 3 min duration is agitated by the pump and for each 60 min the solution with 500 μ *l* was taken out from the tank, and the evaluation by the plaque assaying method was carried out.

2.5 Sterilization of Bacteria E.coli by Circulation Type Equipment

The condition of the cavitation generating equipment is the same as the case of virus. *E.coli* bacteria *XL1-Blue* with the feature similar to water-borne infection bacteria such as Salmonella, was used. At each 60 min, the solution with 500 μ *l* was taken out from the tank, and the evaluation by the colony assaying method was performed.

3. Evaluation of Inactivation and Sterilization

3.1 Inactivation of Virus by Circulation Type Equipment

The inactivation evaluation of a virus on the circulation type equipment is shown in Fig. 4 by comparing two cases for actuator on and off. We observed the reduction of the virus also even if the actuator is not operated. It is thought that a virus cannot increase by oneself and the inactivation occurs by the mechanical stress of a pump. When a vibration is applied, the number of plaques decreased rapidly and the number of plaques decreased to 87 % after 180 min. The existence of a virus was decreasing exponentially and the same result as a reduction of the virus expressed by Eq. (4) was obtained.

3.2 Sterilization of Bacteria by Circulation Type Equipment

The experimental sterilization evaluation of *E.coli* on the circulating type equipment is shown in Fig. 5. In Fig. 5, the horizontal axis is the number of vibration of the actuator. We compared the relative ratios between adding vibration or not. It is clear that the sterilization based on a cavitation action is proportional to a frequency of vibration and the number of times of vibration by operating time experimentally [4,5]. The data in Fig. 5 is expressed with the number of vibration. Since *E.coli* can be increased by oneself unlike a virus, the increase of *E. coli* was observed on the case of no vibration. When the vibration is applied, the cell number of *E. coli* decreased to 18 % at the first step 60 min after the drive start, and becomes 27 and 40 % after 120 and 180 min respectively.

By comparing the decrease of a virus and bacteria, the reduction of a virus is larger than bacteria. A reason is that *E.coli* increases by oneself while the virus cannot increase. Another is that the coat protein which has covered the outside of virus has a weak structure compared with the cell membrane of bacteria. It is thought that radical reaction affects to virus more than bacteria.

4. Evaluation of Bacteria DNA by Electrophoresis Method

4.1 Methodology for Micro Evaluation

In order to verify whether bacteria changed in organization by cavitation generating equipment, the solution after vibration was examined by a electrophoresis method. We classified into four samples shown in Table 2, in which a vibration is applied to the samples E1 and E2. The samples put the solution with 1.0 m***l*** with *E.coli* into a dialysis membrane bag, and

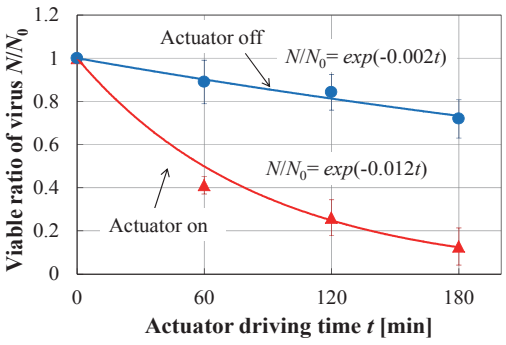

Fig. 4. Experimental result of viral inactivation by circulation type equipment.

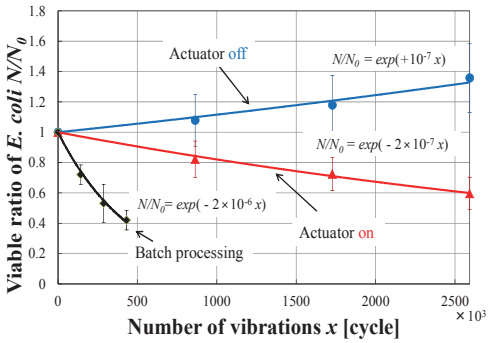

Fig. 5. Experimental result of *E. coli* bacteria sterilization by circulation type equipment.

TiO_2 of 1.0 mm$^{\phi}$ by 5.0 g is added in the samples C2 and E2. The condition of the excitation is a vibrating frequency of 240 Hz, and the 30 min drive duration. While applying vibration by the equipment, the samples C1 and C2 are kept in the dark place. A couple of solutions with *E.coli* was analyzed with the DNA electrophoresis method immediately after vibration.

4.2 Results

The photo of the electrophoresis pattern is shown in Fig. 6. The upper part of the vertical axis in Fig. 6 denotes a large molecular weight, and a lower part is small. The result shows that the band of RNA exists only on the sample E2 which includes both vibration and TiO_2. When the separation enzyme of RNA is added to the sample E2, the band is lost clearly. The result shows that the reaction of radical destroys the membrane of *E.coli* and DNA is flowing outside of the cell. On the contrary, we can not observe the band of DNA for the case E1 with only vibration and it is thought that only the vibration cannot be destroyed but RNA is not detected. It is concluded that the radical reaction is stronger than pulse vibration stress.

5 Conclusion

In this paper, it aimed at the inactivation and sterilization of virus and bacteria by the cavitation pulse power, and the oxidization disintegration of radicals due to the cavitation generating equipment with a giant magnetstrictive actuator. The process mechanism with circulating the liquid for purification was fabricated, and both inactivation and sterilization evaluation by using the equipment was performed experimentally.

We summary as follows,

(1) For circulation type equipment, the number of existence of a virus is decreased to 87 % after 180 min drive time.
(2) For *E.coli* bacteria, the existence ratio is decreased to 40 % after 180 min drive.
(3) When the cavitation generating equipment enables us to circulate through the liquid for purification, the solution with 2.5 *l*, 5 times as much as the container, can be processed as purification.
(4) The formula showing the rate of increase of a virus and bacteria was derived, and it has confirmed experimentally that the number of existence of a virus and bacteria decreased exponentially.
(5) We confirm that the radicals generated by TiO_2 excitation destroy the cell membrane of bacteria and DNA and RNA are flowing out on the outside of a cell membrane

Acknowledgement

This work was supported in part by Grand-in-Aid for Exploratory Research (No.22656067) from Japan Society for Promotion of Science (JSPS).

References

[1] Y. Nozaka and A. Nozaka, *Introduction to photocatalyst*, Tokyo Tosho, 2004, Chp. 7, (in Japanese).
[2] N. Shimizu, C. Ogino, M. F. Dadjour and T. Murata, *Ultrasonics Sonochemistry*, Vol. 14, pp. 184 -170, 2007.
[3] Y. Katou, *Cavitation*, Makishoten, 1990, Chps. 1, 3, 7, and 9, (in Japanese).
[4] H. Suzuki, S. Yamada, M. Kakikawa, Y. Matsumoto and M. Iwahara, "Application of Giant Magnetostrictive Actuator in the Genaration of Radicals," *J. Jpn. Soc. Appl. Electromag. and Mech.*, Vol. 17, No. 3, pp. 142-147, 2009.
[5] T. Suzuki et al., "Action of Cavitation Phenomena Generated by Giant Magnetostrictive Actuator to Inactivation of Phage," *J. Magn. Soc. Jpn.*, Vol. 34, No. 2, pp. 131-136, 2010.
[6] S. Nakamura, T. Suzuki, Y .Ikehata, T. Ueno, M. Kakikawa and S. Yamada, "Inactivation of Virus by Pulse Power Based on Cavitation," *Tech. Meet. Magn., IEE Jpn.*, pp. 1-5, 2009.

Table 2 Conditions for DNA electrophoresis of *E.coli*

Sample	Condition
C1	*E.coli* only
C2	*E.coli* + TiO_2 (1 mmϕ) 5 g
E1	*E.coli* + Driving
E2	*E.coli* + TiO_2 (1 mmϕ) 5 g + Driving

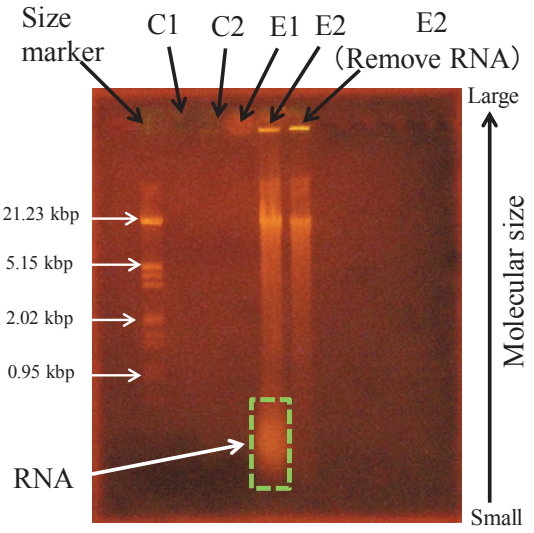

Fig. 6. Result for DNA electrophoresis of *E.coli*.