Application for Marine Industries Using Pulsed Power Technology

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Abstract— Pulsed power is a unique technology which results extreme physical phenomena. Another point is the controllability of output power. For biological application purpose, the time duration of a single pulse lies between a few nanoseconds and a few microseconds, with steep rise and fall time and flatness of its plateau region. It enables application of high pulse electric field and high current in liquid phase, and also can generate discharge plasmas in liquids with a wide range of conductivities. Due to those characteristics, biological applications such as extermination of harmful organisms in highly conductive seawater have been studied for few decades. In this paper, the physical phenomena and application researches on inactivation of bacterial spores, cells, zooplankton, and marine organisms in liquids are introduced. Beneficial experimental results have been reported and the analysis are explained.

Keywords—Pulsed power, electric field, underwater discharge plasma, shockwave, electrical conductivity, sterilization, inactivation

I. INTRODUCTION

Pulsed power is a scheme where stored energy is discharged as electrical energy onto a load in a single short pulsed or as short pulses with a controllable repetition rate. The main characteristic of pulsed power is the extremely high peak-to-average power ratio, so that it can exploit threshold and nonlinear effects. The highest energy and power that have been achieved in a single pulse are the order of 100 MJ and a few hundred terawatts, respectively. Typically, the overall duration of the high-power pulses considered here lies between a few nanoseconds and a few microseconds. Other benefits can be resulted from the short pulse duration, which allows one to exploit time domain or to avoid competing processes with heat losses [1]. Therefore, this technology leads to a variety of innovative researches on environmental, material science, life science and food technology [2-9].

Another unique characteristic of pulsed power technology is: it is possible to apply high pulsed electric field or discharge plasma in liquid phase. Especially, in highly conductive liquid such as seawater. Thus, due to the very fast rise time of applied voltage which is typically several to hundreds nanoseconds. The short voltage rise time enables applying high electric field and large current to a load which filled with highly conductive liquid. Also, it enables to apply high voltages into highly conductive liquid to generate discharge plasma.

Pulsed streamer discharges in liquids is known to generate several physical phenomena: such as extremely high electric fields at the tip of streamers, as well as high energy electrons, ozone, other chemically active species, ultraviolet rays, and shockwaves [10, 11]. Those phenomena are hard to be accomplished with direct current and alternating current. From those points of view, the possibility of using pulsed power technology for marine industries has been explored.

In marine industry, sterilization, exterminating noxious organisms, improving breeding of marine plants and so on. This paper aimed to introduce the unique phenomena caused by pulsed power technology in liquids especially aimed for marine industries.

II. PHENOMENA IN LIQUIDS RSULTED BY PULSED POWER

A. *Pulsed Electric Field (PEF) and Pulsed Current*

When a high voltage pulse is applied to a parallel-plate electrode which is immersed in water, electric field is formed between the electrodes. In this case, the electrical equivalent circuit of liquid can be drawn as a parallel connection of a resistive component, *R*, and a capacitive component, *C*. Thus, the time constant of the parallel-plate electrode, τ, is as equation (1).

$$\tau = RC = \frac{1}{\sigma}\frac{d}{S}\varepsilon\frac{S}{d} = \frac{\varepsilon}{\sigma} \qquad (1)$$

where σ and ε are electrical resistivity and electrical permittivity, respectively. Here, it has to be mentioned that $\varepsilon = \varepsilon_0\varepsilon_r$, where ε_0 and ε_r are electrical permittivity of vacuum and water, respectively. If a higher electric field application between the electrode is required, the applied voltage rise time should be shorter than τ.

In case of tap water, σ is relatively small so that *R* is large. Typically, when σ is given as 100 μS/cm, τ can be calculated as approximately 72 ns. When voltage rise time is shorter than τ, current flow between electrode mainly contains displacement current, therefore, higher electric field can be produced with less joule heating of liquid. Thus, the liquid performs capacitively.

In case of seawater, because it is highly conductive, σ is relatively large so that *R* is small. When σ is given as 20 mS/cm, τ can be calculated as around 360 ps. In practice, it is difficult to generate a high voltage which has rise time shorter than 360 ps. When voltage rise time is longer than τ, current flow between electrodes is mainly resistive current, therefore, electric field can be produced with joule heating of liquid. However, compared with dc source, pulsed power system can apply larger current flow and higher electric field in liquid due to its higher-energy density.

B. *Underwater Discharge Plasma*

The breakdown voltage required to generate discharge plasma in water is around 250 kV/cm to 1 MV/cm depending on voltage polarities, liquid conductivities and electrode

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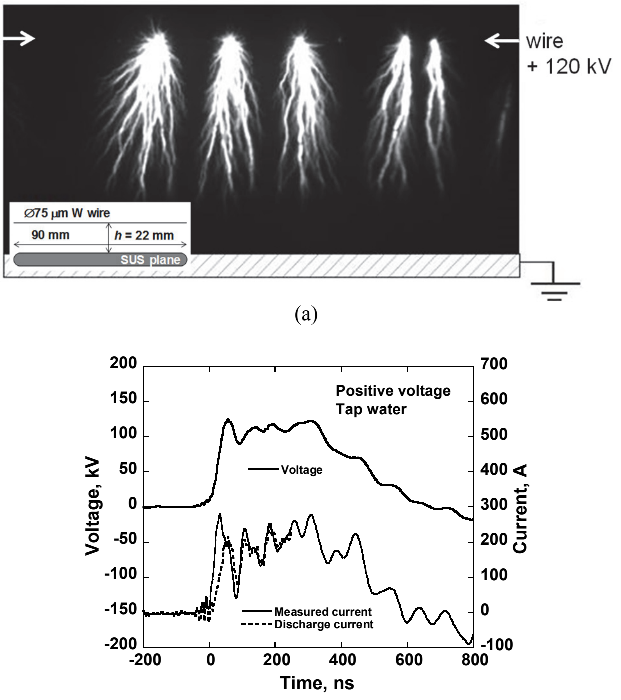


(a)

(b)

Fig. 1. Fast discharges in thin wire-to-plane electrodes which immersed in tap water [14]. (a) Appearance of discharges. (b) Measured voltage and current waveforms.

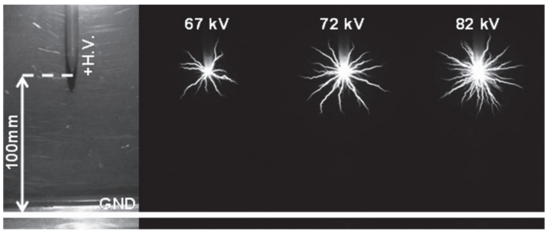


Fig. 2. Discharge images for different applied voltages in needle-to-plane electrodes which immersed in tap water [15].

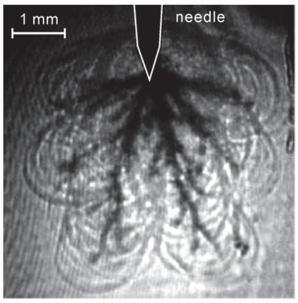


Fig. 3. Time-resolved Schlieren photograph of the root-like streamer discharge emerging from positive needle electrode [16].

geometries [12]. Pulsed power enables generation of such high voltages in water due to its fast rise time. A capacitor bank circuit, Marx generator, magnetic pulse compressor: MPC, and pulse forming network: PFN are typically used to generate underwater discharge plasmas [13].

Fig. 1 (a) shows the propagation image of underwater discharge plasma in wire-to-plane electrodes which immersed in tap water [14]. The streamer propagates from positive charged wire electrode toward grounded plane electrode. In case the wire electrode charged negatively, the streamer doesn’t propagate much in the water. Fig. 1 (b) shows the applied voltage and current waveforms.

When the high voltage electrode is needle configuration, streamer propagates like a ball shape which the center is the tip of the needle. Fig. 2 shows the discharge images for different applied voltages [15]. The temperature of and electron density in the pulsed discharge plasma are 15,000 K and 10^{18}/cm^3, respectively, by using the line-pair method and Stark broadening spectroscopic measurements between point-plane electrodes immersed in tap water [15].

Underwater streamer discharges are accompanied by several physical phenomena such as the generation of extremely intense electric fields exceeding 1 MV/cm, ultraviolet rays, free radical species, and shockwaves. Fig. 3 is a typical time-resolved Schlieren photograph of the root-like streamer discharge emerging from positive needle electrode [16]. The shockwave pressure is much higher than that in gas phase and is important for marine industries. A measurement study reported that the pressures exceeding 1 GPa occur near the streamer discharges when pulsed positive voltages applied to a needle electrode [16].

III. APPLICATIONS USING PULSED ELECTRIC FIELD AND PULSED CURRENT

A. *Inactivation of Spores*

The intent of food pasteurization with PEF is to induce the dielectric breakdown of the cell membrane, not the dielectric breakdown of the fluid inherent in the food [17]. When the applied electric field produced a potential difference of 1 V across the cell membrane of a microorganism, the cell lysis occurs. This means an irreversible loss of the membrane’s function as a semipermeable barrier between the cell and its environment [18-20].

E. Coli is a typical bacterium which used for sterilization studies. It can be killed by heating at 75 degree Celsius for 1-minute. On the other hand, bacterial spores are highly resistant and difficult to inactivate because the dormant structures are formed in response to adverse environmental conditions [21]. A study of inactivation of spores using PEF in a pressurized flow system is reported [17]. PEF with a maximum magnitude higher than 110 kV/cm and a pulse width of 100 ns generated by MPC has been applied to a carefully designed treatment chamber through which a suspension fluid of 0.5 MPa continuously flows. Using the proposed PEF inactivation method, maximum 6.7 log reductions were achieved for *B. subtilis* spores (see Fig. 4). These reductions were much greater than those obtained by a heat inactivation approach. Through frequency analysis using the frequency components of the applied pulses and the frequency response of the equivalent circuit of the spore, it was found that most voltage is applied to the outside of the core in the lower frequency and to the inside in the upper frequency (see Fig. 5). Also, transmission electron microscope micrographs of *B. subtilis* spores were taken to verify the effect of the PEF treatment. Fig. 6 shows that after exposure to heat, the color of the cortex gets slightly dark and some deep dark spots in the core appears probably due to the leakage of some materials from the core.

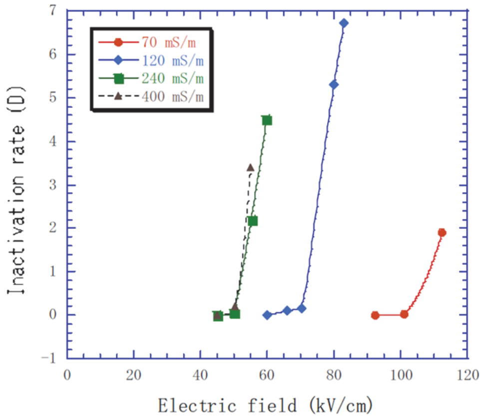
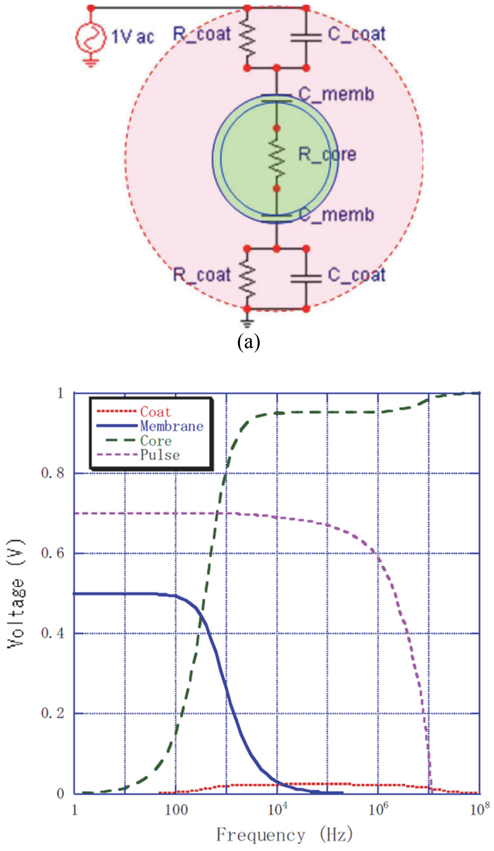


Fig. 4. EF inactivation of B. subtilis showing the dependence on the electric field [17]. (D-value refers the time to reduce the spore population by 90%.)



(a)

(b)

Fig. 5. Frequency components of the applied pulse are also described in an arbitrary unit [17]. (a) Simplified equivalent circuit. (b) Frequency response of the spore.

After exposure to PEF, the cortex gets much darker and the deep dark spots in the core can be clearly observed, which are caused by the irreversible loss of the inner membrane's function. These results explain the higher inactivation rate of spores can be obtained by using the PEF treatment method than the heat treatment in liquids.

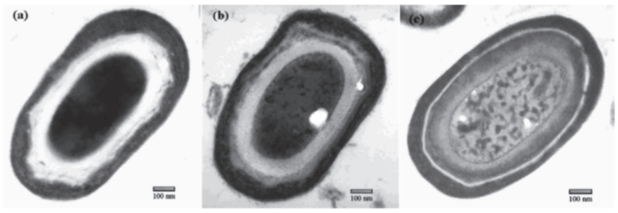


Fig. 6. TEM micrographs of B. subtilis spores showing the spore cross-section characteristics. (a) Control, (b) heat treatment (121 °C), and (c) PEF treatment [17].

B. *Effects of PEF on the embryonic development of Medaka fish (Oryzias latipes) eggs [22]*

Fertilized ovum of Medaka fish is often used for embryonic development, since embryo direct and maternal indirect exposure routes can be examined and most are transparent, facilitating microscopic observation [23]. It has been reported that applying short (less than 100 ns) pulses increased the possibility of electric field interactions with subcellular structures, which leaded to secondary cellular events, such as temporally increase in cell membrane permeability and induction of apoptosis. However, the effect is not only aimed for inactivation, some studies are carried out for find the effects of short pulsed electric field in-vivo during embryo development.

An MPC was employed to generate 0.5 to 20 kV pulses with 50 to 300 nanosecond pulse durations. Fertilized eggs of d-rR medaka were used, and the age of the experimental eggs were 6 hours, 1 day and 2 days post fertilization. In each experiment, a single medaka egg (about 1.2 mm diameter) was set at the middle of a 2 mm or 4 mm width cuvette and a single electric pulse was applied. After the experiments, the eggs were observed under a microscope until they hatched or died. A fluorescent plasma membrane integrity indicator, propidium iodide (PI), was used to study electroporative uptake kinetics of the embryo cells after the electric pulse exposure. By applying 300 ns electric pulses, extensive damage of eggs was observed immediately after pulse application. Fig. 7 shows the results of hatching rate at 15 mS/cm conductivity medium. The applied voltage had 20 ns of rise time and 45 ns of pulse duration. After applying over 37.5 kV/cm of electric field, all of 1 and 2 days eggs died. For shorter 50 ns width pulses and low electric field, delayed hatching consistent with electric field intracellular interaction was observed, whereas stronger electric field affected the eggs immediately after the pulse and those eggs could not survive and died a few days later. The short electric pulse was effective to produce intracellular effect consistent with longer hatching time for low conductivity experiments. The delayed uptake of PI and the low PI expression for the low electric field experiments indicated the temporary poration of the blastomere with the possible intracellular effects. For the high conductivity experiments, the short electric pulse damaged the embryo of older eggs. This was confirmed with the high uptake of PI. For lower electric field, delayed PI expression for the new laid eggs were observed, which made it appropriate to change the cells differentiation and proliferation.

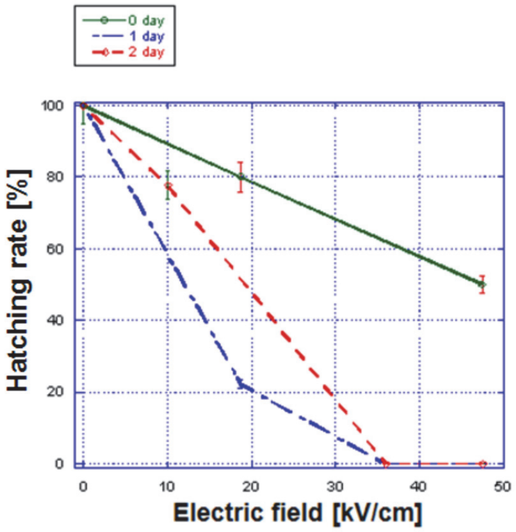


Fig. 7. Hatching rate of each electric fields at 15 mS/cm conductivity medium [22].

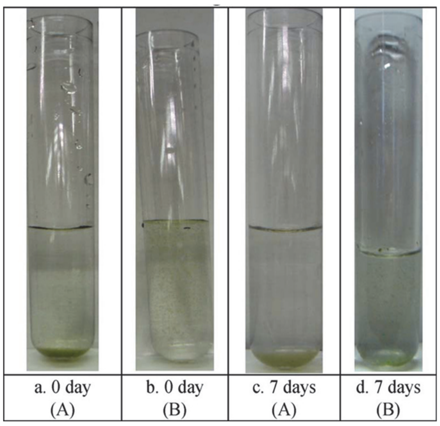
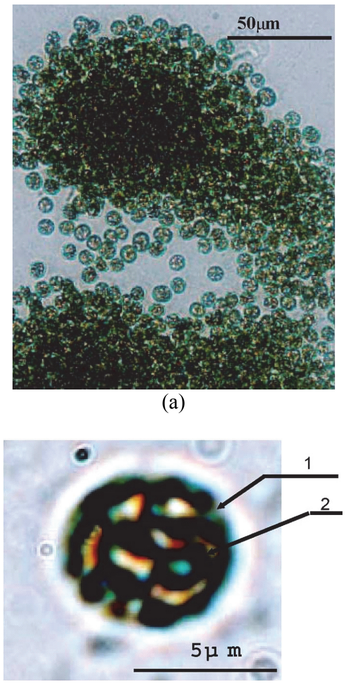


Fig. 9. Cultured M. aeruginosa cells with and without applying discharge. (a) and (b) Appearances of the cultured cells at the very moment when the cells were put in the medium. (c) and (d) Appearances of the cultured cells after one week, where "A" means after applying discharge and "B" means without applying discharge [24].



(a)

(b)

Fig. 8. (a) Colonies of the M. aeruginosa cells, (b) Single cell, where 1: mucilaginous sheath and 2: gas vesicles [24].

IV. APPLICATIONS USING UNDERWATER PULSED DISCHARGE PLASMA

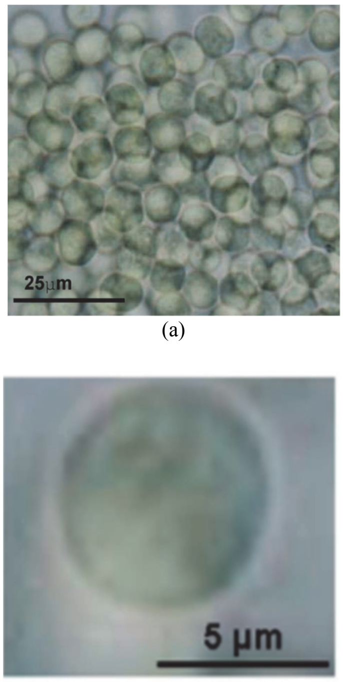
A. *Inactivation of Cyanobacteria Cells (Algae) [24]*

Cyanobacteria (often referred to as blue-green algae) are members of a group known as eubacteria or true bacteria. They are a frequent component of many freshwater and marine ecosystems. When a bloom dies in a pond or shallow lake, severe oxygen depletion can produce objectionable odors and even cause fish kills. Some cyanobacteria produce substances which are extremely toxic and can cause serious illness or even death if consumed. From the microscopical observation, it was confirmed that the small green particles were the colonies of cyanobacteria cells, which is 3.2 - 6.6 μm in diameter, is a typical genus of toxic cyanobacteria (see Fig. 8).

A Blumlein-type pulse-forming network (B-PFN) was employed to provide a 2 μs, 160 kV pulse voltage to a point-to-cylinder electrode geometry and generate a high electric field and formed streamer discharge in cyanobacteria contained water. The streamer-like discharges spread from the positive needle electrode toward the ground cylinder electrode and did not shift to an arc discharge. The diameter of the discharge area was about 100 mm.

Fig. 9 shows appearances of the cells collected from discharge chamber before and after discharge applications. In Fig. 9, "A" means with discharge application, "b" means without discharge application. "0 day" means soon after taking out from discharge chamber, "7 days" means cells cultured for 7 days after taking out from the discharge chamber. It was observed that *M. aeruginosa* cells, after applying discharge, have changed color from green to yellow after one week (see Fig. 9 a and c). It can be said that the cells were dead and became rotten. In contrast, the cells, without applying discharge, were still living after one week (see Fig. 9 b and d). There are two possible reasons of death of the *M. aeruginosa* cells after applying discharge. One is the streamer discharge, which led to the death of the cells. The other is the discharge which weakened the cells, and the cells were catabolized by other bacteria or plankton in the sample water.

Fig. 10 shows the bright-vision photomicrographs. In the result of the comparison of Fig. 8, the gas vesicles (GVs) in the *M. aeruginosa* cells disappeared after applying discharge because GVs were collapsed by the pulsed streamer discharge. Since the discharge did not spread to the entire space of the discharge chamber, radicals cannot diffuse far away in the water column, and the UV radiation did not seem to play a role either. Therefore, free radical's formation and ultraviolet radiation are not considered as the main factors for GVs breakdown. As a conclusion, the shockwave and discharge



(a)

(b)

Fig. 10. *M. aeruginosa cells appearances after applying discharge. (a) Color appearance of the cells; (b) Single cell appearance [24].*

current due to the pulsed streamer-like discharge in water are the effective factors for the GVs collapsed, and the *M. aeruginosa* cells sank to the bottom of the discharge chamber. The pulsed streamer-like discharge will become one of effective options for cyanobacteria blooms treatment.

B. *Inactivation of Zooplankton [25, 26]*

A combination of micro bubbles and discharge plasma has been studied for Artemia (brine shrimp) treatment. A large number of micro bubbles are generated by injection of a pulsed power (0.41 MW, 1 μs) into water solution with 5.7-wt% sodium hydrogen carbonate ($NaHCO_3$) as an additive (see Fig. 11). The diameter of the bubbles is estimated to be 23 μm which is half of that obtained without the additive. The number density of the bubbles with the additive is 6 times as high as that obtained without the additive.

It is found that 98 % of the larva of Artemia are successfully inactivated by firing 800 injections of pulsed power into water solution with the additive, which is 1.6 times as high as that obtained for the water solution without the additive (see Fig. 12). The gross energy efficiency for inactivation reaches 0.25 million larvae a kWh. It indicates that a large number of micro bubbles generated by the injection of pulsed power are effective to inactivate the zooplankton in the water.

C. *Inactivation of Nymphonella Tapetis: Sea Spiders [27]*

Nymphonella tapetis (sea spiders) are bivalve-infesting Pycnogonida which seriously damage bivalves in their massive proliferation time. An effective killing method hitherto not established. By applying underwater pulsed discharge, 480 J/pulse, all the adult *N. tapetis* placed in a sphere shape reactor were dead. Legs and body of *N. tapetis* were cut and severe damaged (see Fig. 13). The alimentary canal became hollow-shaped and no body fluids flows were observed on the treated *N. tapetis*. Those results indicate that *N. tapetis* were killed by the underwater generated discharge resulted shockwaves. Experiments were also carried out in different mediums: sands filled seawater and bivalves placed in the sands filled with seawater. In all cases, 100 % of death ratio are obtained.

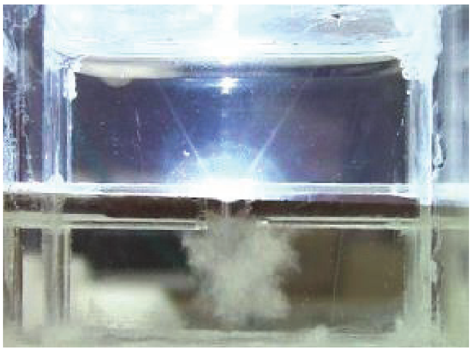


Fig. 11. Expansion of bubbles generated by injection of pulsed power in water [25].

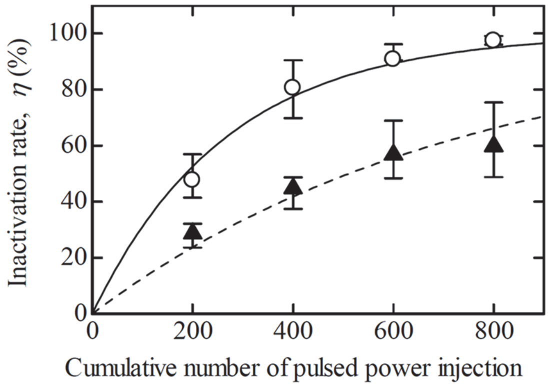


Fig. 12. Inactivation rate of larvae of Artemia in tap water (▲) and tap water with 5.7-wt% NaHCO3 additive (○) [26].

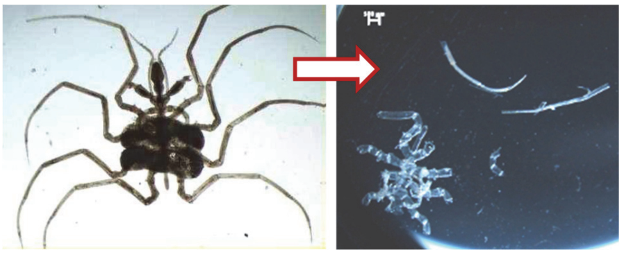


Fig. 13. Typical images of *N. tapetis* before and after applying pulsed discharge generated shockwaves in seawater [27, 28].

V. CONCLUSION

The conventional electrical systems such as dc or ac power supply are not great with high voltage application to seawater. Thus, the seawater is highly conductive therefore the applied electrical power mainly consumed as heating loss rather than effective utilization in the liquid.

In this paper, the features of pulsed power technique, underwater discharge generation, studies of inactivation of bacteria, cells, eggs and organisms in liquids are introduced. Following is the summary of the contents:

1) The time constant of the parallel-plate electrode which is immersed in liquid can be calculated as approximately 72 ns and 360 ps for tap water and seawater, respectively. Voltage rise time should be shorter than those values in order to apply high electric field in the liquids with less thermal heat.
2) Underwater discharge plasma can be generated in both tap water and seawater using pulse voltages with fast rise time. Typically, the temperature of and electron density in the pulsed discharge plasma are 15,000 K and $10^{18}/cm^3$, respectively. The shockwave pressure exceeding 1 GPa occur near the streamer discharges when pulsed positive voltages applied to a needle electrode.
3) Inactivation of *E. Coli*, bacterial spores, cyanobacteria cells, zooplankton, and marine arthropod can be exterminated using pulsed high electric field or underwater discharge generated shockwaves.
4) Lower pulse electric field enable the change the differentiation and proliferation of fertilized ovum of Medaka fish.

Some other studies focused on activation of marine biological objects are omitted from this paper, but they have been shown to be beneficial. From above, pulsed power is a useful tool for marine industries and leaves room for further investigations.

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