Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2013.780795

51 (2013) 6224–6229
September

Taylor & Francis
Taylor & Francis Group

Plasma production by multi-phase alternating current underwater discharge and its applications to disinfection of micro-organisms

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Received 11 October 2012; Accepted 11 December 2012

ABSTRACT

This work is concentrated on providing a novel way to produce underwater plasma. The underwater plasma is generated by taking advantage of a multi-phase alternating current voltage source with the frequency of a commercial electric power system. The multi-phase underwater plasma source is composed of 3-phase transformers to supply 12-phase alternating current voltage, a voltage regulator to control the output voltage of the transformers, capillary electrodes, and a water vessel for installation of the capillary electrodes. This arrangement can provide the stable, large-scale underwater plasma by giving the capillary electrodes independent powers without voltage drop due to phase difference made from the voltage source. This plasma system in flowing water would be useful as a continuous massive water treatment for the purification, sterilization, or disinfection of objects or materials.

Keywords: Underwater discharge plasma; 12-Phase transformers; Water treatment system; Capillary discharge

1. Introduction

Water pollution is a major issue which is a leading cause of deaths and diseases around the world. In order to sterilize water contaminated by various environmental factors such as pathogenic bacteria, micro-organisms, etc. [1,2], various approaches such as UV release [3], microwave irradiation [4], electrolysis [5], filtration [6], pulsed arc discharge [7], etc. have been investigated. For example, the membrane filtration system removes floating matter, bacteria, and various ions more than 99.9%. Also, the recent development of a functional membrane showed the enhancement of permeability, which is a drawback in membrane system. However, the membrane system is not flexible in wide ranges of temperature, pH, and pressure, due to the nature of membrane material. Therefore, these filtration techniques alone do not meet the criteria in a limited space [8], needing the back washing of the installed filter and the change of a new membrane. In general, ozone shows the significant sterilization effect

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Presented at The Fifth Desalination Workshop (IDW 2012), October 28–31, 2012, Jeju, Korea

against bacteria and viruses. In addition, the organic particles and chemicals in water can be eliminated through coagulation or chemical oxidation [9]. However, ozone in water contaminated with organic materials is not stable and does not show the continuous effect for sterilization. The UVGI method uses a short wavelength (especially 254 nm) in ultraviolet region that is harmful to micro-organisms. It is effective in destroying the nucleic acid in these organisms so that their DNA is disrupted. This removes their reproductive capabilities and kills them [5]. At this condition, the efficiency is not good due to low penetration of ultraviolet. The electrolysis, which is the most popular water treatment method, uses low amounts of energy, can achieve good sterilization effect in a short time. It forms lots of chlorine-containing chemical species [10,11], showing the significant sterilization capability. However, there are disadvantages such as the erosion of electrode and the release of toxic gases. Several reports have reported regarding plasmas that are generated via direct current or alternating current discharge near water by making use of a metal electrode and a water-grounded electrode system [12]. Compared with these approaches, the underwater capillary discharge system in this work not only can eradicate micro-organisms, but also has latent advantages in terms of the device portability, utility cost, and discharge controllability in a wide range of water conductivity settings [13]. This work is focused on purifying waste water [14] by an underwater plasma.12-phase alternating current voltage source produces an underwater plasma by providing an efficient breakdown voltage for the electrodes connected in parallel [15]. Electrical discharges on or in the liquid can contribute to produce significant amount of active plasma chemistry reactions and make a considerable number of reactive radicals (OH, H, O, etc.), ultraviolet light, shockwaves, neutral molecules (H_2O_2, O_3, O_2, etc.), and ions [2,16].

In an effort to disinfect bacteria, commercial water treatment applications such as chemical treatments, UV radiation, and ozone injection for potable water delivery systems have been used. The chemical treatments such as chlorination can render potable water toxic, and UV radiation and ozone injection have also been proven to be two practical methods of bacterial inactivation in water. Plasma methods effectively combining the contribution of UV radiation, active chemicals, and high electric fields are considered, therefore, to be a very effective approach to water treatment.

For a long time, many studies of water discharge plasma formation have investigated corona, streamer, and arc discharges supplied by pulsed high voltages, direct current voltage and alternating current voltage using metal electrodes [16–21]. These power sources can be faced with voltage drops on all of the parallel connected electrodes in case of producing underwater plasmas by the simple parallel connection to single ac or dc power supply. Also, the output power can be concentrated on one electrode resistance variation, which can be caused by the electrode erosion or deformation, temperature change of the surrounding water of electrode, and so on. Therefore, the stable, uniform plasmas from the multi-electrode cannot be obtained. In this report, 12-phase alternating current voltage sources with the frequency of a commercial electric power have been developed perfectly to produce the stable, independent, uniform underwater discharge plasma by means of the 12-phase ac power supply. This study proposes the use of a multi-phase discharge to effectively sterilize undesirable contaminants such as Enterohemorrhagic *Escherichia coli* (EHEC; *E. coli* O157:H7).

2. Experiments and discussion

This study suggests the novel way for the production of stable underwater plasma by means of the 12-phase ac power supply. Fig. 1 shows the circuit of 12-phase ac power supply over the three phase transformers. As shown in Fig. 1(a), the circuit is composed of three steps. In the first step, a 3-phase voltage controller is used to regulate the output voltages. A balanced 3-phase commercial power source, which has three equal voltages which are $2\pi/3$ rad out of phase with one another, is provided to the controller. In the second step, a Δ-Y-configured 3-phase transformer (380 V: 380 V) induces two kinds of 3-phase voltage sources with $\pi/6$ rad out of phase for each corresponding component by connecting three outputs to four pairs of 3-phase transformers. The first kind of 3-phase voltage source is gained from three outputs between one terminal and another terminal. The other kind of 3-phase voltage source is attained from three outputs between the neutral point n and each secondary terminal, which is identical both in phase and in magnitude to the 3-phase voltage source of the primary side. However, it is $\pi/6$ rad out of phase but identical in magnitude to the first kind. In the last step, a 12-phase voltage source is accomplished; of which each component has identical magnitude and $\pi/6$ rad out of phase with adjacent components. One pair of a 6-phase voltage source (V_2, V_4, V_6, V_8, V_{10}, and V_{12}) is obtained by using two pairs of Δ-Y-configured 3-phase transformers whose windings are opposite; the phase difference between two 3-phase transformers is π rad. The other pair of a 6-phase

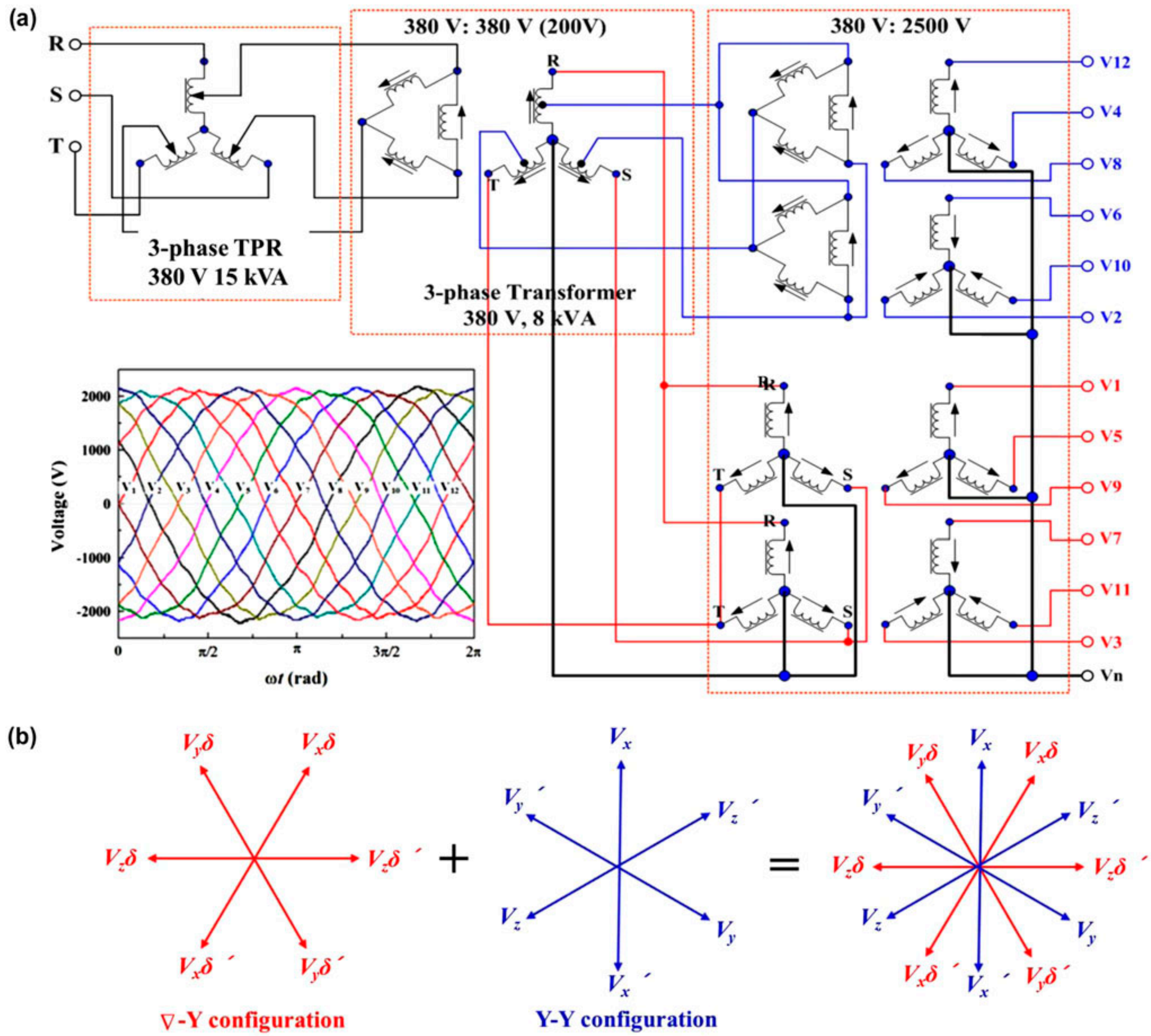

Fig. 1. (a) Schematic presentation showing the equivalent circuit of a 12-phase ac power supply made up of several 3-phase commercial electric transformers. The inset is the waveform measured from the 12-phase ac power supply at an arbitrary voltage. (b) Phasor diagrams illustrating the relationship between 3-phase and 12-phase system.

voltage source (V_1, V_3, V_5, V_7, V_9, and V_{11}) is obtained by using two pairs of Y-Y-configured 3-phase transformers whose windings are opposite. Eventually, this arrangement provides the 12-phase ac voltage source, as shown in the inset of Fig. 1(a). The voltage waveforms in the inset were attained at an arbitrary voltage. Fig. 1(b) shows the phasor diagrams illustrating the relationship between 3-phase and 12-phase systems. The 12-phase voltage driving source in Fig. 1(a) can be established from the summation of two vectors (Δ–Y and Y–Y configurations), as shown in Fig. 1(b). Eventually, each of 12-power lines with $\pi/6$ rad out of phase is connected to the electrodes arranged in parallel.

Fig. 2(a) is the picture showing the experimental setup for the 12-phase alternating current underwater discharge. The power supply in Fig. 2(a) consists of several 3-phase transformers as shown in Fig. 1(a). The 12 high voltage lines were connected to 12 capillary electrodes in Fig. 2(b). The high voltage probe and the current meter were employed to measure the discharge voltage and the discharge current, respectively. Fig. 2(b) is the picture showing the stable underwater capillary plasmas produced by the

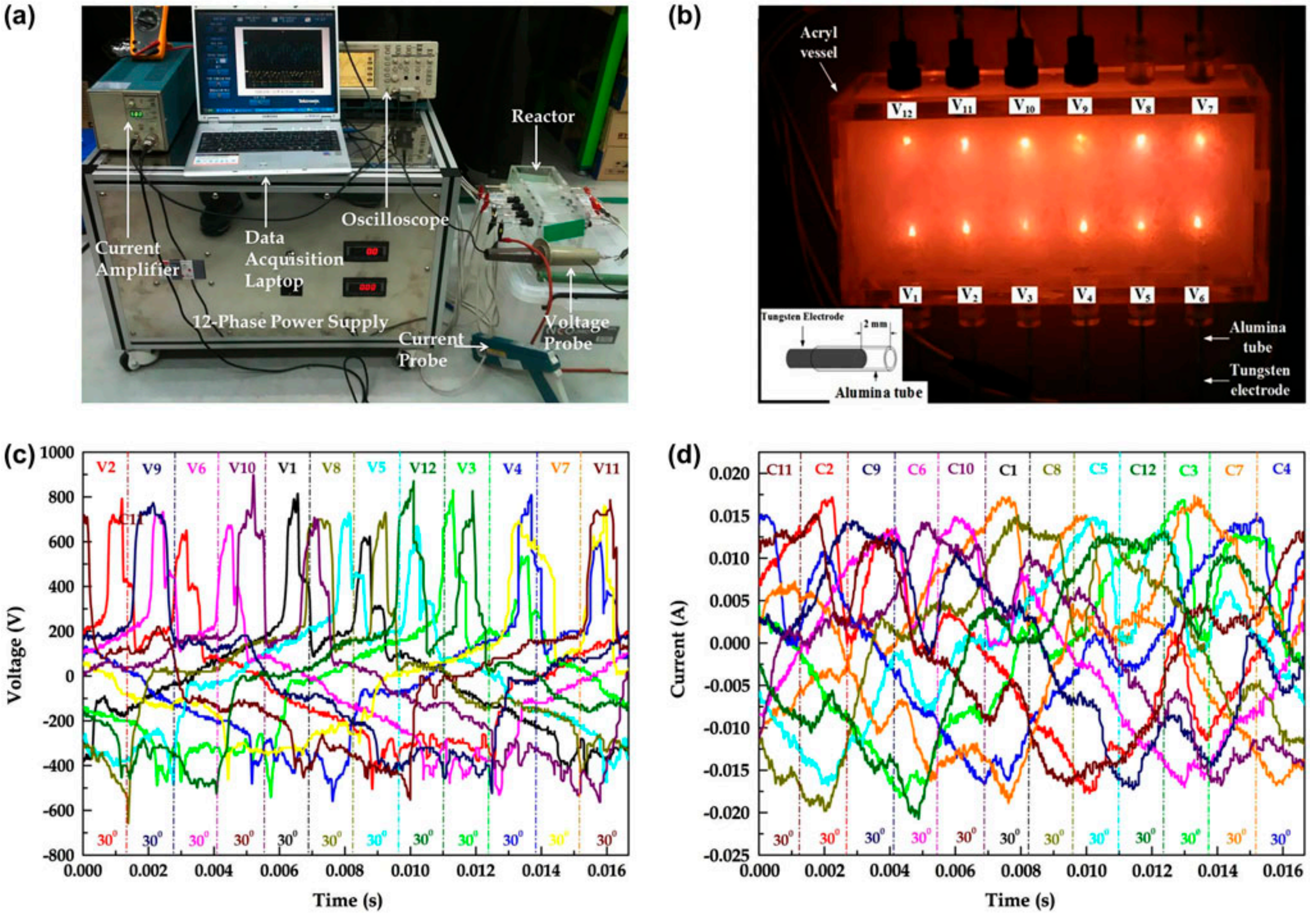

Fig. 2. (a) The experimental setup for the12-phase alternating current underwater discharge. (b) Underwater capillary discharge plasmas generated by the 12-phase ac power supply. (c) Voltage waveforms corresponding to 12-phase capillary discharge. (d) Current waveforms corresponding to 12-phase capillary discharge.

12-phase ac voltage driving source. In this test, water with the conductivity of 53 mS/cm was used. For the formation of the capillary discharge plasmas in water, 12-capillary electrodes were installed in a reactor made of acryl, as shown in Fig. 2. The electrode used here was a tungsten electrode with a diameter of 2 mm. It was inserted into alumina tube with an inner diameter slightly larger than 2 mm. Here, water served as a ground electrode. The inset of Fig. 2(b) displays the configuration of the capillary electrode in detail along with the distance *d* between the ends of the tungsten electrode and the alumina tube (here, *d* is 2 mm). The outputs from the 12-phase power supply were connected to 12-capillary electrodes, supplying independent, stable power for each electrode. The mechanism of plasma discharge and breakdown in this case is bubble process and an electronic process. The bubble process starts from a microbubble which is formed by the vaporization of liquid from local heating and ohmic heating in the strong electric field region at the tips of electrodes. The bubble grows, and an electrical breakdown takes place within the bubble. This arrangement provides a novel method to form underwater plasma in water [13]. The voltage and current waveforms of the 12-phase high voltage source were showed in Fig. 2(c) and (d), respectively. In a one cycle of commercial frequency (60 Hz), there are accurately 12 times of discharge with 30°. It can make plasma stable regardless of the electrode erosion or deformation, temperature change of the surrounding water of electrode in water.

Fig. 3 shows the disinfection curve of *E. coli* treated by means of the capillary discharge plasma in seawater and FAC concentration. In this experiment, we used Enterohemorrhagic *E. coli* O157:H7 (Korean Collection for Type Culture; KCTC) known as EHEC to prove the extinction efficiency against harmful pathogenic bacteria. EHEC was grown with tryptic soy broth (Difco Laboratories, Detroit, Mich.) containing 50 μg/ml nalidixic acid (Sigma Chemical

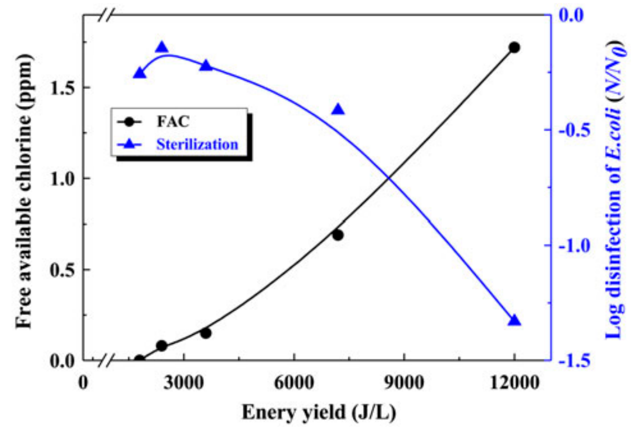

Fig. 3. Disinfection curve of *E. coli* treated by means of the capillary discharge plasma in seawater and FAC concentration.

Co., St. Louis, Mo.) and 0.1% dextrose (Sigma Chemical Co., St. Louis, Mo.) at 37˚C for 24 h [22]. Bacteria sample was inoculated in 1-liter seawater bath. The number of bacteria colony-forming units (CFU) was enumerated by using serial dilution-agar plate method. Briefly, 1 ml of each collected liquid sample was serially diluted in 9 ml of sterile peptone water until it reaches 10^{-9} of serial dilution factor, and is spread on agar to count colonies and documented in CFU. The graph in Fig. 3 shows the disinfection of *E. coli* and increase of FAC concentration along with the energy yields. The underwater plasma reactions create free available chlorines (FACs) which are known to be the major bactericidal agent in the electrochemical sterilization. In proportion to the concentration of FAC, the disinfection rate of *E. coli* is increased. Sterilizing effect of FAC has been studied in many different publications [23,24], and also reported by the Center for Disease Control and Prevention that 0.25 ppm of chlorine concentration killed more than 10^7 of *E. coli* O157:H7 in 30 s [25]. The mechanism of bactericidal effect of FAC can be explained in many different ways including high pH (hydroxyl ions action) which interferes in the cytoplasmic membrane of bacteria and also phospholipid degradation in lipidic peroxidation. Moreover, it is reported that FAC inactivates essential enzymatic sites of bacteria [26].

3. Conclusion

This study reported the plasma production in the capillary electrodes by 12-phase ac voltage driving source and the disinfection of micro-organisms. We have developed a 12-phase ac voltage driving source by using commercially available 3-phase transformers, which solved the problems from the parallel connection of multielectrodes to one power supply. The underwater discharge makes the best use of the treatment of waste water and sterilization of polluted water with micro-organisms. The water discharge system showed the killing more than 107 times for *E. coli* O157:H7 in 30 s. It is expected that the bactericidal effect of the underwater plasma can be further utilized in various different purposes which need large amount of sterile water. Further research is of course necessary to clarify the limitations as well as the capabilities of this method in practical applications. We have the necessity of testing various pathogens (spore-forming bacteria like *Clostridium sporogenes*, and well-known pathogens like *Staphylococcus aureus, Salmonella typhimurium, and Listeria monocytogenes*) to provide the bactericidal effect of underwater plasma.

Acknowledgment

This work was funded by 2011 National Agenda Project of the Korea Research Council of Fundamental Science and Technology. Also, this work was partially supported by the National Research Foundation of Korea Grant funded by the Korean Government (Grant #2010-0029422).

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