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Electroporation for Water Disinfection: A Proof of Concept Experimentation

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***Abstract*—This paper is a proof of concept showing the effectiveness of using irreversible electroporation (IRE) as a stage of water disinfection in the water treatment process. The IRE process essentially requires relatively high voltage pulses to pose a pulsed electric field across harmful microorganisms. In this paper, a laboratory-based solid-state Marx generator was built for this purpose and untreated water samples have been used to test the effectiveness of applying variable pulse width, magnitude and rate. All the pulses are unipolar rectangular. The tested samples are all from the same water source with the same coliform count. After performing the electroporation disinfection process the coliform count reached zero proving the effectiveness of IRE.**

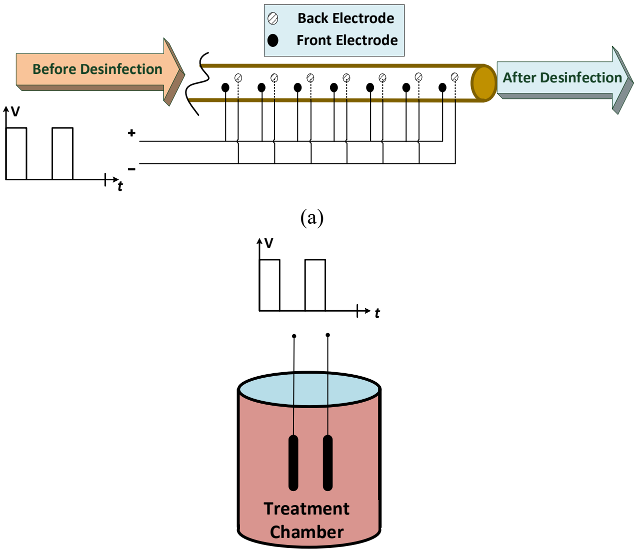
Keywords— Coliform, Electric Field, Electroporation, Marx Generator, Power electronics, Pulsed Power, Voltage Pulses.

I. INTRODUCTION

Amongst the water treatment process chain, disinfection and pH correction are the final processes that water undergoes. It is a buffer-less operation, as it is performed on the live outflow from the works and then put directly into supply, leaving no room for error. The disinfection process targets harmful microorganisms such as bacteria. Bacteria are generally measured in coliforms per 100ml, for drinking water, the UK regulations stated that only 0 count per 100ml (also denoted Non-detectable) is considered safe for consumption [1]. As a result, a successful disinfection process should result in zero-count coliform per 100ml of water. The choice of disinfection method is commonly based on initial water quality and the year the site was built and can be varied.

The main types of water disinfection are ultraviolet, chlorination, and ozone [2]. Despite alternatives, the water disinfection process is still dominated by chlorination as the most effective method. Both ultra-violet and ozone methods require additional chemical disinfection as there is no residual disinfection to prevent contamination during distribution. On the other hand, chlorination needs to be reduced to a safe level post-disinfection (typically between 0.1− 0.3 mg/l) [3]. It can be concluded that although these well-established methods are very effective, the process chain is complicated, expensive and requires post-treatment adjustments to ensure that the chemicals are of a safe level for human consumption.

In this paper, a relatively new concept is proposed, the concept as highlighted in Fig. 1 is based on applying pulsed electric field (PEF) across the water can lead to harmful microorganisms disinfection.



(a)

(b)

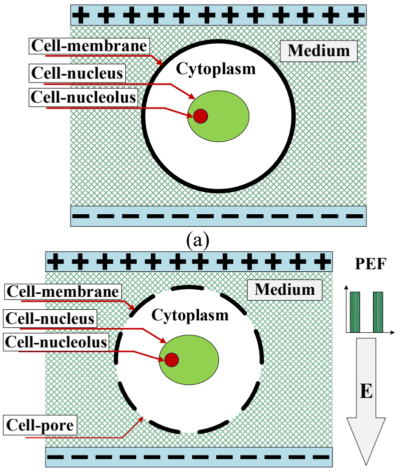
Fig. 1. Methods for applying pulsed electric field for water disinfection: (a) Electrodes attached to the discharge pipe. (b) Treatment chamber.

Although well-established theoretically, no practical implementations exist. This paper aims for bridging such a gap. Water PEF disinfection can be carried out by two methods namely: electrodes attached to pipes or treatment chamber-based electrodes as illustrated in Fig. 1a and Fig. 1b, respectively. No chemical substances are required to perform the disinfection. Moreover, the PEF is primarily produced from pulsed voltage, as a result, the process is conservative in power consumption and can be powered from a standalone renewable power source (e.g. an off-grid solar panel). The rest of this paper is organised as follows: Section II will provide the theoretical base behind the electroporation process, section III will introduce the used solid-state Marx Generator and the experimental results will be summarised in section IV.

II. ELECTROPORATION

Any microorganism is comprised of cells built from 3 main components: cell nucleus, cell cytoplasm, and cell membrane [4]. Creating pores in the microorganism cell-membrane using PEF is called electroporation [5] as can be seen in Fig. 2. This can be reversible, where the cell survives after PEF removal, or Irreversible (IRE) where the cell ceases after PEF removal. The IRE is the type considered for water disinfection.

Raw water carries many pathogens and harmful bacteria which could cause anything from mild sickness to severe health complications and even death if ingested, making treatment vital to ensure safe water consumption. The main component in the electroporation process is the voltage pulse generator (PG). It is worth noting that, although continuous voltage (i.e., DC voltage) can be utilised, it will be inefficient from the electric power consumption perspective. Therefore, pulsed voltages are adopted in the electroporation process [6]. Pulsed voltages will expose PEF across the treatment sample, the strength of the PEF can be controlled by controlling the voltage pulse width, peak and repetition rate [7]. This is application dependent.



(a)

(b)

Fig. 2. Process of electroporation: (a) Biological cell before applying PEF. (b) Biological cell after applying PEF.

III. SOLID-STATE MARX GENERATOR

In the open literature, there exist many power electronics-based pulse power generators (also called solid-state pulse generators) that can perform effectively for the water disinfection process [8]. They can vary in terms of controllability, flexibility and footprint. Moreover, they supersede the traditional high voltage (HV) pulse generators dominated by Marx generators and pulse-forming networks [9]-[10]. Comparing and developing an effective pulse generator falls beyond this paper's scope. As a result, a solid-state Marx generator (SMG) is built for this experiment. The topology schematic is provided in Fig. 3. As in the traditional Marx PG, in the SMG the capacitors are charged in parallel through the $'S'$ switches while discharged in series through the $'T'$ switches. Across the load R, a rectangular unipolar pulse is formed with a peak voltage of v_P, repetition frequency of $f_s = 1/T_s$ and pulse width of t_{pl} as depicted in Fig. 4. The peak of the voltage pulse is equivalent to the voltage sum of the utilised modules, for 4 modules charged from $V_s = 250\text{V}$, $v_P = 4 \times V_s = 1$ kV. The capacitors are recharged to V_s voltage during the pulse zero time.

For the sake of this paper, the laboratory-based SMG was formed of 4 identical modules, the single module schematic is given in Fig. 5a while the assembled module is shown in Fig. 5b. Fig. 5c shows the SMG in an isolated casing containing the 4 modules along with the fibre-optic drivers and the terminal leads. The parameters of the module components are given in Table I. Each module is capable of withstanding 600V, therefore the maximum obtainable pulse peak is 2.4kV.

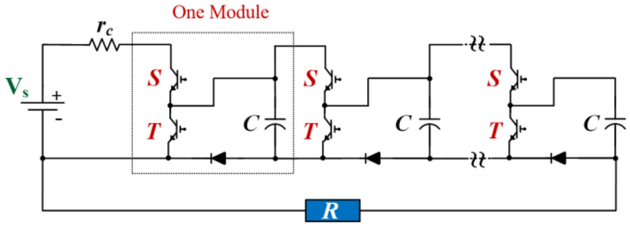


Fig. 3. Schematic diagram of the solid-state Marx Generator.

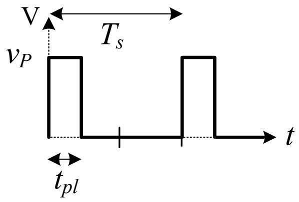
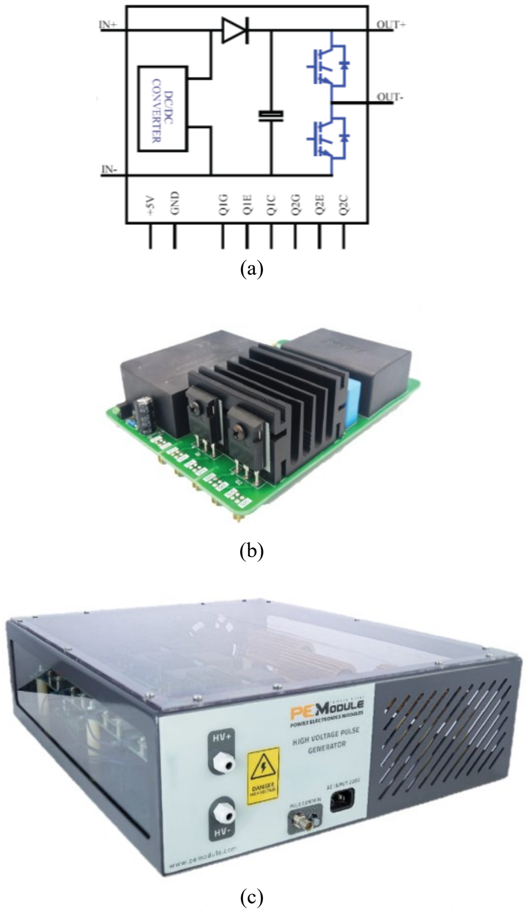


Fig. 4. Typical unipolar rectangular voltage pulse.



(a)

(b)

(c)

Fig. 5. Implementing a 4-module SMG (a) One module schematics. (b) One assembled module. (c) overall SMG with the associated casing.

TABLE I. SMG PARAMETERS

Component Name	Rating
Input AC supply	230V
Input DC supply	Min 100V−Max 600V
Module Silicon Carbide (SiC)×2	1200V/17A (C3M0160120D)
Module Ultrafast Diode×1	1200V/15A (STTH1512PI)
Module capacitance×1	20μF, Film Capacitor

IV. EXPERIMENTATION

In this section, the constructed test chamber, experimental setup and results are summarised.

A. *Water Treatment Chamber*

As depicted in Fig. 6a, the test chamber is comprised of a 1000ml glass beaker with a non-conductive plexiglass cover. Three holes are created in the cover, two for holding the stainless electrodes with 85mm separation and one for mounting a thermometer. The chamber is sufficient to perform the experiment trials on the utilised 500ml water samples. Moreover, 85mm separation is enough to be well below the 30kV/cm breakdown strength of the air.

B. *Water Samples*

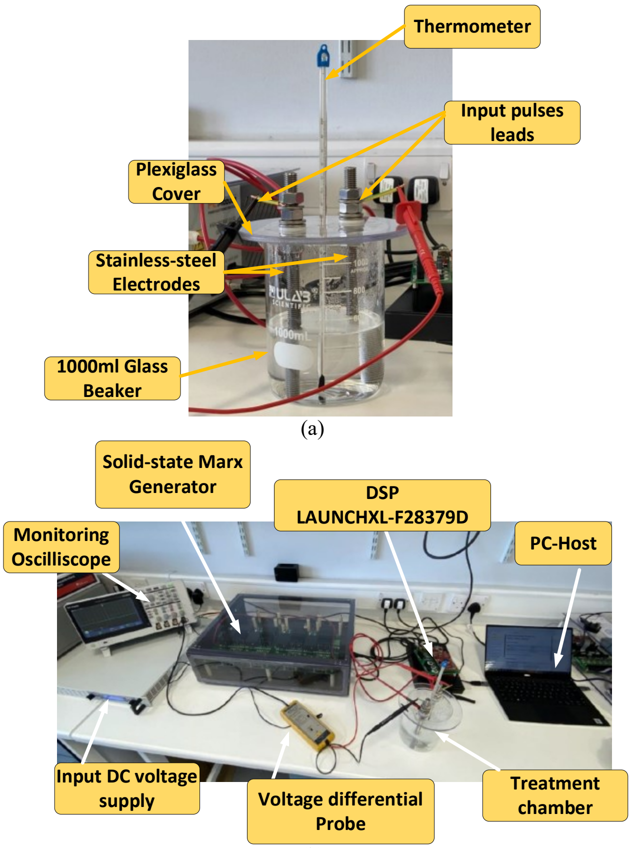
The samples were taken post-filtration pre-disinfection from Baddinsgill Reservoir in Edinburgh, Scotland. Eight samples each of 500ml have been prepared for electroporation disinfection test in addition to a control sample. The control sample will be used as a reference for the coliform count. Each sample has its unique serial number. The samples have been collected and sent to a third-party lab for coliform count results after finalising the disinfection treatment within 4 hours delivery window.

C. *Experimental Setup*

As illustrated in Fig. 6b, the pulse generator's output pulse width and frequency are controlled by a digital signal processor (DSP). On the other hand, the pulse magnitude is limited to 1.4kV due to differential probe capabilities. Since the used SMG has 4 units, each unit is charged with DC voltage of 350V. Therefore, the DC voltage input source is regulated at 350V. The terminals of the SMG are connected to the test chamber electrodes after adding the water sample. The generated pulses are monitored by an oscilloscope to make sure the correct pulses are generated.

D. *Experimental Steps*

Each one of the eight test samples has been subjected to a specific voltage pulse. The variety of voltage pulses was selected to analyse the post-disinfection process on several aspects namely: Water temperature (°C), supply withdrawn electric current (A) and coliform count (CFU/100ml). Based on the controlled sample, the coliform count of the water samples is around 46 CFU/100ml. All the samples started the disinfection process at 8℃ and the utilised 500ml water equivalent resistance as per the described treatment chamber is 10kΩ. The experimental trials are classified into four groups as detailed in Table II.



(a)

(b)

Fig. 6. Experimental Rig. (a) Treatment chamber. (b) Set-up.

E. *Experimental Results*

In five out of the eight trials a 100% disinfection was achieved, this is shown in Table III. It is clear that the wider the pulse and the higher the voltage peak the more effective the disinfection will be, as shown in trials 1C, 2B and 4B. Nevertheless, the electric current withdrawn from the supply will be increased significantly. This indicates two things: first, the treatment time can be shortened for this specific case (4B as an example); second, the resistance of the water is reduced while the disinfection process takes place. It can be concluded as well, for the same pulse width, the 10μs as an example, the disinfection time can be further shortened when applying a high repetition rate while still having moderate water temperature. On the other hand, halving the treatment time at the 1kHz rate failed to reach 100% water disinfection.

TABLE II. EXPERIMENTAL TRAILS DESCRIPTION AND GROUPING

Group	**1**			**2**		**3**	**4**	
Subgroup	***A***	***B***	***C***	***A***	***B***	***A***	***A***	***B***
Application Time (T_a)	10min			5min				
Pulse Repetition rate (f_s)	1kHz					10kHz		
Pulse Voltage (V_p)	1.4kV						700V	900V
Pulse Width (t_{pl})	1μs	10 μs	25 μs	10 μs	25 μs	10 μs	40 μs	40 μs
Notes	Group 1 aims to test the effect of pulse width on the disinfection process based on the described aspects in Section *IV-D*			In group 2, the same steps of group 1 were repeated only for the wider pulses at a shorter time. Again the three aspects were monitored and compared		Group 3 explored the effect of a faster repetition rate and it will be compared with the case of 2A against the monitored aspects.	Group 4 is dedicated to the effect of voltage pulse magnitude at longer pulses and fast repetition rate, The three main aspects were monitored and compared.	

TABLE III. OBTAINED RESULTS POST DISINFECTION

Group	**1**			**2**		**3**	**4**	
Subgroup	***A***	***B***	***C***	***A***	***B***	***A***	***A***	***B***
Water temperature (℃)	59	68	95	24	30	52	46	60
Supply current (A)	0.77	0.95	1.3	0.35	0.75	2.1	2.27	2.9
Coliform count (CFU/100ml)	0	0	0	20	10	0	3	0
Percentage disinfection with respect to the control sample.	100%	100%	100%	52%	76%	100%	96%	100%

V. CONCLUSION

This paper presented an experimental trial for water disinfection using electroporation. It aims to bridge the water disinfection gap between the available theoretical and scarce practical. The designed experimental trials explored the treatment time with a variety of unipolar rectangular pulse rates, magnitudes and widths. Analysing the obtained results shows the effectiveness of the process in general. However, for more efficient electroporation reduced current needs to be drawn from the power supply. Additionally, the water temperature needs to be kept within acceptable levels. Higher repetition rates of relatively short pulses can lead to very effective and satisfactory results in a short application time. Conversely, wider pulses at lower peak voltage will result in higher temperatures and less efficient power consumption. It can also be concluded that the low repetition rates will require longer application time to assure successful disinfection. In summary, the electroporation method is not only effective but also clean and environmentally friendly, it can be applied within a container reservoir-based electrodes or via distributing electrodes along the water flow pipe. Nevertheless, it is recommended to add chlorine to ensure that the residual chlorine levels follow the drinking water regulations, as to ensure post-treatment protection. On the energy front, generating the voltage pulses can be obtained from an off-grid solar panel which allows flexible and sustainable operation.

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