Pulse Power Applied to Process Industry and Environment

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Invited Paper

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Abstract: Pulsed power application has emerged to become an important technology in today's industry beyond defense sectors, although historically the applications included particle acceleration, imploding plasmas and related. Pulsed power refers to the technology where a steady accumulation of energy followed by its rapid release, results in the delivery of a large amount of instantaneous power over a very short period of time. By releasing the stored energy over a very short interval a huge amount of peak power can be delivered to a load. The focus of this paper is on the pulsed power applications to process industry and environment; which include processing of fruit juices, beverages and dairy products along with water treatment and alleviation of air pollution problems.

Introduction

The need for pulsed power has arisen due to the increased demands for compactness with equipment or the system, and to target the energy to a specific area. For example, it is highly necessary to use pulse electric field in electroporation of cells suspended in high conductivity media to avoid any thermal effects [1-8]. Pulsed power is also attractive considering the energy savings and to achieve reliable repetitive operations in some practical applications. Some examples include; generation of pulse width modulated voltage waveforms for adjustable speed drives, and in excimer lasers for lithography [9-10].

The basis of pulsed power is to convert a low peak-power, long duration input power into a high peak-power, short duration pulse. Based on the energy requirements, repetition rate and the operating voltage, either gas filled or solid-state semiconductor switches can be used to direct the pulsed power as required. It can be said that those applications requiring high hold off voltages and high current with fast switching times require gas-phase switches. Further, in these switches plasma allows transport of very high currents at relatively low power dissipation. Spark-gaps, thyratrons, and pseudo-spark switches are some of the common types of gas-filled switches used in high energy density plasma physics applications, and high power microwave sources [11-12]. Gas spark gaps have been used to operate voltages in excess of 1 MV and 100s of Coulombs with pressures > 1 atmosphere. Whereas, thyratrons and pseudo-spark switches operate below atmospheric pressure. For high repetitive pulse applications, thyratrons filled with hydrogen (< 0.5 torr pressure) are preferred as the hold-off voltage can be as high as 100 kV with a few kA peak currents. The limitation in the current capacity is rather due to cathode that relies on thermionic emission with thyratrons. For higher currents with fast switching at high repetitive rates, pseudo-spark thyratrons are preferred as they use a combination of field emission and thermionic emission [11-12]. The switching times, that is the rise time for the pulse is extremely short with any of the gas-filled switches; <5 ns for spark gaps to ~ 25 ns for pseudo-spark switches, with ~ 30 to 50 ns for thyratrons.

In the recent past, advances in the semiconductor industry have lead to development of switching devices with relatively higher voltage and current ratings [1-2, 13-15]. Compared to gas-filled switches, the semiconductor switches offer many advantages like, improved stability, high reliability, lower cost and simpler triggering. As such, pulsed power applications have expanded into fields like biotechnology, environment, and medical applications. Since, solid-state devices do not have as high voltage/power ratings as compared to thyratrons;

they are stacked in series and parallel to obtain the required voltage/power ratings. Hence, the new trend has been to use power semiconductor devices in packages which further assure compact designs and easy mobility.

Based on the physics of switching operations, each type of solid-state switch offers a range of power capacity, voltage rating, and frequency of operation. Figure 1 illustrates the features available with different devices. The thyristors can switch in a large power at a very high voltage, but the switching frequency is the lowest among all the semiconductor switches. The metal oxide semiconductor field effect transistors (MOSFETs) and insulated gate bipolar transistors (IGBTs) can operate at a significantly higher frequency, but their power handling capacity is low compared to gas-filled switches. On the other hand, the MOSFETs are substantially faster than IGBTs (typical switching time: 200ns for an IGBT, 20ns for a MOSFET), but IGBTs are more efficient at high voltage (less losses), cheaper per kW switched, and are being manufactured at higher voltage ratings (up to 6500V); whereas, the MOSFETs are limited to 1200V. In addition, devices like IGBTs and MOSFETs exhibit not only a fast turn-on feature, but also a relatively fast turn-off feature. The relatively newer switches like MOS-controlled thyristors (MCTs) are considered as gate drive devices similar to MOSFETs or IGBTs with significantly high power handling capacity. Likewise, IGCTs (Integrated Gate Commutation Thyristors) are gaining attention as one of the promising alternatives for high-voltage high-power switching applications.

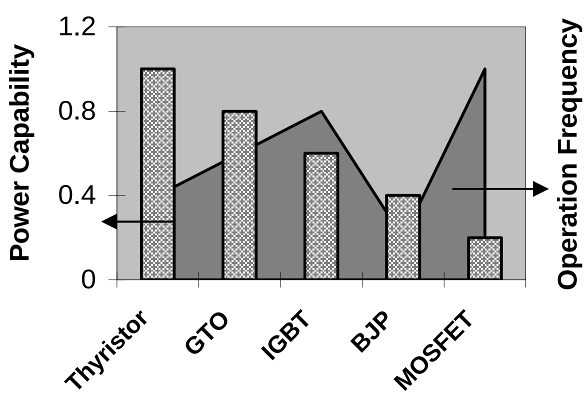


Figure 1: Features available with different solid-state devices.

Energy Storage Devices

The high voltage power supply provides the energy that is to be stored in the energy storage device, which is either a capacitor or an inductor. Pulsed power supplies that use inductive storage devices are not in the scope of this paper, but References [1,2,13] provide good reviews. The capacitors used in pulse generations have undergone many design changes themselves, and it is now possible to find a self-healing feature that extends the life of capacitors under harsh pulsed conditions [2]. Research into energy storage dielectrics has resulted in the development of very high energy density materials that allow the capacitors to store more energy in small packages. The energy is stored in the capacitor until the pulse is needed at which time the switch must close. When this happens, the energy goes through a pulse compression stage or multiple stages, where the total energy is discharged in a short time. The ideal case would be that all of the energy that is put into the systems is at the output; however, this is not the case, because real devices have parasitic losses. Good designs make use of circuit techniques to minimize these losses. One example is impedance matching, which is a condition for maximum power transfer.

Circuit Topologies

Gas-filled switches such as thyratrons are still being used because of their high voltage capabilities and fast turn-on times. With a thyratron switch, the turn-on time is controllable, but the turn-off time is dependent on the RC time constant of the load resistance and the energy storage capacitor, leading to an exponential-decay pulse. A schematic illustration of a typical thyratron switched pulse generator is shown in Figure 2. The major components of the pulse generator are: a high voltage cap-charger (or a regulated DC source), a current limiting resistor, fast operating thyratron switch, charging capacitor and the load. Sometimes, a pulse shaping or pulse forming network (PFN) can be introduced to achieve a desired pulse shape. Thyratron-based pulsed power supplies can use a PFN in order to deliver a square pulse; however, the PFN can only be tuned to a single pulse width. Modifications are required for each pulse width that is required.

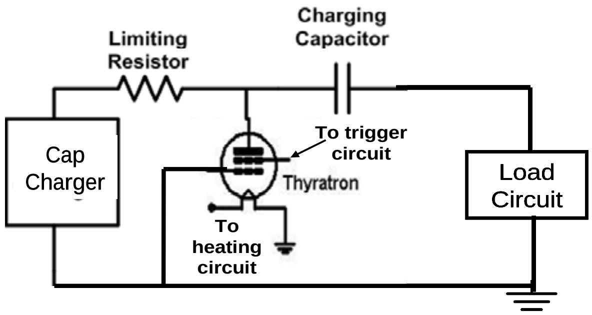


Figure 2: A schematic of a thyratron-based pulsed power supply.

A high pulse repetition rate can be obtained by using the topology illustrated in Figure 3, wherein, the high voltage DC source has been eliminated. The conversion from line AC into a DC voltage is carried out at a low voltage, and using a high voltage pulse transformer and a thyratron, very high repetitive pulses of high voltage can be generated. The circuit topology has been used to generate as high as 10,000 pulses per second of 40 kV peak.

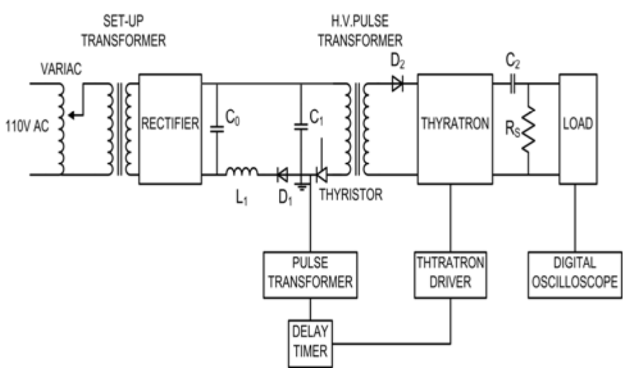


Figure 3: A schematic of a high repetition thyratron based pulsed power supply.

Semiconductor Switched Pulsed Generators

Often, very high repetitive pulses of variable pulse amplitudes, or a very steep front flat top square pulses are required. In such applications, the solid-state (semiconductor) switched pulse generators are sought after. In the following sections, a basic scheme for MOSFET and IGBT based circuit configurations are discussed (Figure 4).

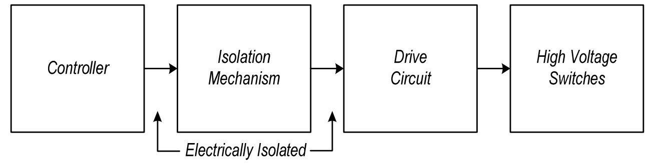


Figure 4: An illustration of solid state device based pulser topology

The four main parts of the pulser are: the controller, the isolation mechanism, the drive circuit, and the high voltage switches. The controller sends the gating signal through the isolation mechanism to the driver circuit, which then provides the current to properly drive the switches. The operation of this pulser requires the use of a series connected chain of switches to allow the device to operate safely at higher voltages. Several switching topologies have been designed to produce square pulses of both uni-polar and bi-polar signals using solid-state devices, with amplitudes up to 10 kV. One such design was used to build a MOSFET-based pulser for an investigation into electroporation-mediated delivery of the 3.3-kb pGFPuv plasmid DNA molecule into the pathogenic bacterium *E. coli* O157:H7 successfully [15]. For higher voltage and power ratings, IGBT-based pulsed power generators are preferred. The circuit topology generally follows a similar scheme that is presented in Figure 5; although some aspect of the circuits could be different. Figure 6 depicts a chain of square pulses generated using IGBT-based pulsers.

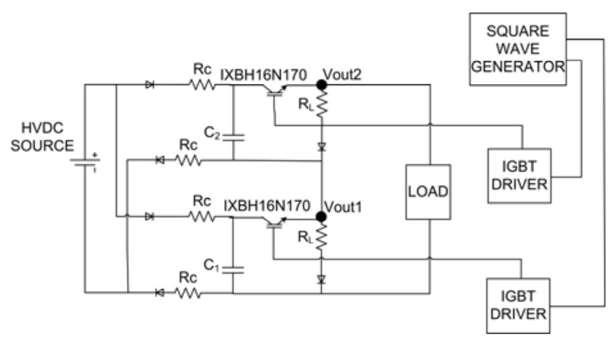


Figure 5: A schematic of a cascade type square-wave pulse generator showing two stages.

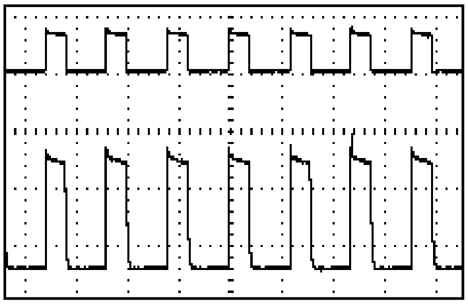


Figure 6: Train of square pulses generated by a four-stage cascaded pulser (Figure 5). Upper waveform, at the output terminal of the first stage, and the lower waveform is at the last (fourth) stage terminal. Scale: x-axis: 500V per division and y-axis: 500 μs.

Pulse power Applications

Improvements in food quality and the safety of processed foods are the most important features in any food processing technology that can meet the needs of the consumer and enhance competitiveness in global markets. Food producers are looking for solutions to prevent the growth of microorganisms in food without compromising the initial quality of products. Most remarkable are the preservation processes whereby products are subjected to a physical treatment at temperatures much less than those required for heat pasteurization. Consequently, the initial quality of products is no longer adversely affected by heating. In addition, use of preservatives is less frequently required to extend the shelf life of products. Thus, in the past few years, many emerging food processing technologies that use minimal or no thermal energy have been investigated [16-30].

Currently, heat treatment methods are extensively used to extend the shelf life of food products by killing spoilage microbes that might grow under conditions they normally encounter in storage. However, heat treatment methods are energy intensive and adversely affect nutritional and organoleptic quality of the processed foods. Irreversible loss of fresh flavour, loss of aroma and texture, and initiation of undesirable browning reactions in juices, are some of the unwanted changes the food undergoes during heating and cooling cycles [31]. In the case of milk, the denaturing of milk proteins is also a concern with heat pasteurization [32-36]. Since the primary goal is to avoid the adverse effects of heat on the treated foods, the food processing industries are particularly interested in these new technologies [37].

Alternative Food Processing Technologies:

To improve the food quality and safety, including extended shelf life, some of the alternative technologies that have been considered to have high potential for commercialization are high pressure processing (HPP) [38], pulsed electric field (PEF) treatment [26-28], and use of ultra violet (UV) light. Often, some of these techniques can be used in combination, or as supplementary processes with heat treatment. When used in combination, the process temperature can be significantly lower than 70 ^{o}C, which is the pasteurization temperature.

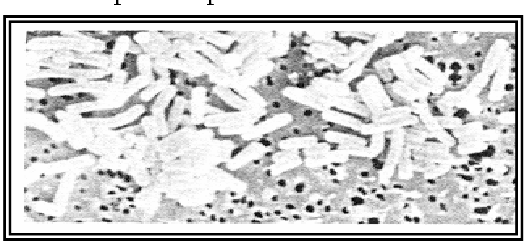
Although HPP is one of the earliest technologies available it is not considered as common as heat treatment. The drawback with HPP is its high cost and batch operation. UV light is commonly used in the disinfection of water; however, to achieve the required high level of microbial inactivation, the UV radiation exposure must be at least 400 J/m^2 in all parts of the food product. The main drawback with UV is the depth of penetration of the radiation, and as such, the method is preferred for surface treatment of various foods. Alternatively, dielectric heating, which includes RF and microwave heating, is used in pasteurization, but it is a thermal method as opposed to HPP, PEF and UV treatments. Denaturing of the main components of food protein is another major concern with both dielectric heating and UV treatment.

The pulsed electric field technology is an attractive alternate as it is a non-thermal method, in which pulse energy is transmitted across the product through a high field effect. The treatment involves the application of high voltage, short duration pulses to the food, which is passed between the high voltage and ground electrodes, so as to induce a substantially high field across the microbial cell membrane. Some of the important benefits that can be expected with this new technology are improved quality of the processed food in terms of nutritional value, flavour, taste and appearance, and extended shelf life. The basic concept is to target the energy supplied to the product by applying an intense high-voltage but a very short duration pulse, in the range of tens of nanoseconds to a few microseconds duration, to inactivate microbial contamination. Also, this technology can offer high quality, “fresh” foods along with improved shelf life. Needless to say, the method can be energy efficient due to the nature of pulsed electric field, and the microbial destruction occurs due to the high field effect rather than due to current effects; thus the possibility of any Ohmic heating of the treated food is reduced significantly. Furthermore, PEF technology can be used in complement with heat treatment at much lower temperatures (< pasteurization temperature of 70 ^{o}C) and or with high pressure effects so as to explore the synergistic effects between the coupled processes.

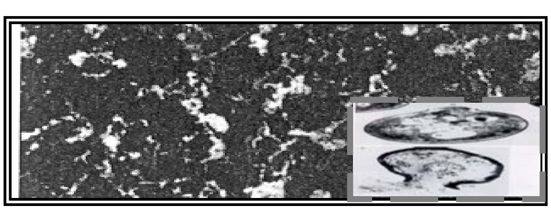
Pasteurization using PEF Technology:

Review articles [39-40] extensively cover key scientific developments related to PEF processing, including basics of electroporation and cell membrane breakdown. Beyond a doubt, it has been proven that irreversible breakdown of the cell membrane occurs if the applied field is above a critical value, although the theory of the breakdown mechanism is still controversial. The illustration below (Figure 7) describes the microbial inactivation by electroporation.

The PEF method proposed here involves the application of high electric field (15-80 kV/cm) with very short duration (hundreds of nanoseconds to tens of microseconds) across a certain electrode geometry that contains the food. Using a thyratron switched high voltage pulse power supply; we have been able to generate exponential decay pulses in the range of 0 - 40 kV, ~ 30ns rise time at a repetition rate of 400 pulses per second.



Before Pulse Application



After Pulse Application

Figure 7: An Illustration of bacterial cells inactivation by means of electroporation.

Attempts have been made to improve upon the design of treatment chambers by many researchers; modified versions of cylindrical and parallel plate electrode systems [14, 28]. Field enhancements and dead-zones within the treatment chamber are some of the major concerns with the existing chamber designs. The treatment chamber described here addresses the identifiable deficiencies of current treatment chambers, Figure 8 [41]. The electrode geometry consists of a toroidal outer electrode and a spherical inner electrode giving a uniform treatment zone without any edges. A schematic of the overall PEF treatment scheme consisting of pulse generation and treatment zone is described in the illustration below. The treatment zone not only provides a highly uniform electric field distribution, but also allows for uniform exposure of the sample to be treated to the maximum field. In addition, only a portion of the food prior to PEF exposure can be heated to elevate the sample temperature as opposed to raising the temperature of the entire bulk. This is a feature to be exploited for thermal and PEF synergistic effect. Also, as can be visualized, the inter-electrode-region has no edge effects; rather it provides a highest field zone between smooth electrodes.

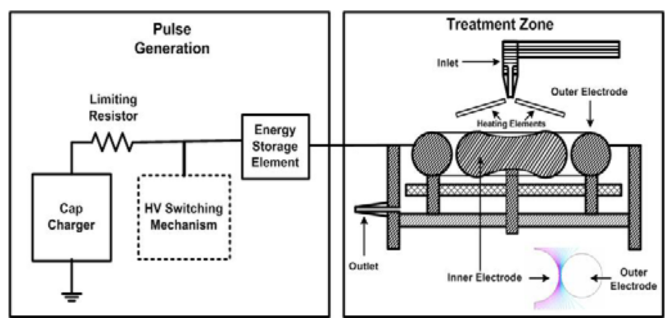


Figure 8: A PEF system to process liquid foods.

PEF Test Results:

With respect to using PEF for microbial inactivation, much of the work done to date involves application of PEF across suspensions of microorganisms in buffer solutions, or artificially contaminated foods [22, 29]. Microorganisms of known species are grown separately, and inoculated into the sample before the PEF tests. In such treatments, a high level of inactivation has been observed, up to 8 log cycles depending on the microbial contamination and the type of suspension. Only a few researchers have tried to inactivate microorganisms that are naturally grown in real foods [37, 42] where it has been observed that achieving a reduction in microbial contamination by greater than a 3-log cycle is a difficult task, although not impossible. A greater reduction in count can be achieved when PEF is combined with the addition of antimicrobials such as lysozyme, nisin or with heat [21-22]. Further, pulsed electric field processing of milk has recorded impressive results by inactivating a single species of food pathogen in a homogenous system, but it is doubtful if such a setting is realistic to indigenous milk borne microbes to mimic a practical heterogeneous microbial community that may exist in practice [42].

Both freshly squeezed and contaminated (aged) orange juice samples were treated under different PEF conditions. The results of the effect of PEF on both the naturally contaminated and inoculated microorganisms are depicted in Table 1. Regardless of the age of the orange juice (aged or freshly squeezed), a 2-3 log cycle reduction in microbial count have been obtained depending on the test conditions, although for naturally contaminated juices it is difficult to inactivate microorganisms using only PEF. Thus to study the possible synergistic effect of temperature along with PEF, the juice samples were pre-heated by an Infra Red (IR) source to about 45 °C then pulses were applied immediately. The comparison of colony count between the treated juice at room temperature and at 45 °C is also shown in Table 1. Despite the reduction of the applied voltage pulse (voltage reduced from 14 to 12 kV) due to the increase in the electrical conductivity, a greater kill was achieved at the elevated temperature, with half the number of pulses compared to the results obtained from room temperature tests. It is important to note that the test temperature, 45 °C had no significant effect on inactivation, in the absence of PEF treatment.

In addition, the effects of PEF on inoculated microorganisms have also been conducted. For these experiments, microorganisms were collected from the stored juice and inoculated into previously pasteurized orange juice. The initial colony count was about 10^7, which is close to the colony count of the stored orange juice sample. It is evident that a greater kill can be achieved for inoculated microorganisms compared to naturally growing ones.

Table 1

Treatment of orange juice using PEF at 23°C and 45°C

Number of pulses/mL	Electric field level (kV/cm)	Count (log cfu/mL on PCA	Count (log cfu/mL) on PDA
Effect of number of pulses on the reduction of microorganisms in aged orange juice			
Not treated	N/A	7.91	7.01
30	46.7	6.60	5.31
60	46.7	6.37	5.70
120	46.7	5.93	4.94
Effect of number of pulses on the reduction of microorganisms in fresh orange juice			
Not treated	N/A	5.88	5.25
30	46.7	4.49	4.15
60	46.7	4.16	3.81
120	46.7	3.77	3. 60
Effect of temperature on the reduction of microorganisms in aged orange juice			
Not treated	N/A	7.91	7.01
23° C	46.7	6.37	5.70
45° C	40.0	6.20	4.84

Pulsed electric field processing of milk have recorded impressive results by inactivating a single species of food pathogen in a homogenous system [6, 20, 24-25, 34], but it is doubtful if such a setting is realistic in our view. It is therefore interesting to assess the potency of variable electric field strength and pulse numbers on a heterogeneous microbial community (*Escherichia coli* plus milk-borne microbes), as it is a step towards formulating optimal bioprocessing strategies for efficient PEF processing of milk.

Freshly pasteurized milk purchased locally was incubated at 30°C for 10 hrs to allow the indigenous mixed-culture microbes to grow exponentially to the desired population (10^4 – 10^6 cfu/mL). The *E. coli* (ATCC11229) contaminated milk sample was prepared by introducing a known concentration of the bacterium into 10 hr-old milk sample to give the desired bacterial population. The samples were subjected to selected pulsed electric field treatment with a field intensity ranging from 10 – 40 kV/cm and pulse numbers varying from 10 – 120/mL. Figure 9 shows the effect of inoculum size of *E. coli* plus indigenous microbes while Figure 10 shows the effect of inoculum size of indigenous microbes alone. There was 0.6 – 1.7 log reduction of bacteria within the first 30 pulses when the inoculum size was higher than 5.1 log in both communities, but 0.05 log reduction at 4.2 log inoculum. However, microbial inactivation by way of log reduction gradually increased to 1.5 for *E. coli* plus indigenous microbes, and to 2.2 log for indigenous microbes at 120 pulses.

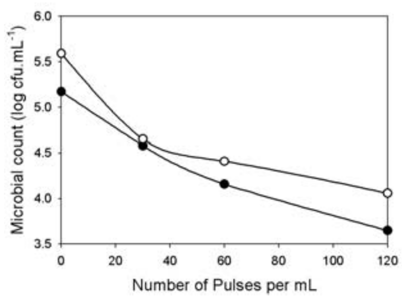


Figure 9: Microbial count of *E. coli* plus indigenous microbes as a function of number of pulses.

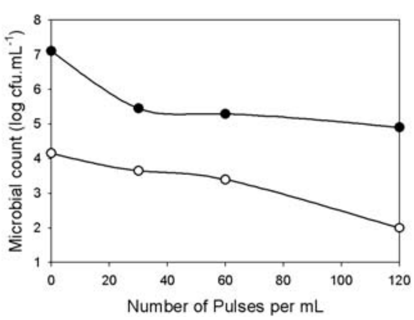


Figure 10: Microbial count of indigenous microbes as a function of number of pulses.

It is evident from the above results that the antimicrobial potency of pulsed electric field is a function of electric field strength as previously reported [18, 34-35], but our findings indicate that microbial community compositions also affect the potency of pulsed electric field inactivation of microbes in milk. Although Alvarez et al., [19] have observed that microbial inactivation is not a function of initial cell concentration (inoculum size), Selma et al. [36] have claimed strain, inoculum- size and product parameters affect potency of pulsed electric field, the result of our investigation seems to explain the discrepancy. The antimicrobial potency of PEF may or may-not be affected by inoculum-size depending on the number of pulses and field strength applied. Microbial inactivation (decreases) is affected by inoculum-size when we applied few pulses (less than 30 pulses/mL in our case, Figure 3-5) as observed by Selma et al. [36], but not at 120 pulses/mL as we later did nor at 200/mL in the case of Alvarez et al.,[19].

PEF Technology applied to Environment

The increases in the demand for clean potable water and clean air with stricter environmental regulations have raised interest in the development of safe water treatment technologies as well as emission control. Disinfection of water is highly essential in order to reduce the number of waterborne diseases. Disinfection methods for potable water, that are in practice today range from use of chemicals like chlorine to ultraviolet (UV) light. But, pathogens like *Cryptosporidium* are resistant to conventional drinking water disinfectants, including chlorine. If used in excess, chlorine poses environmental and health concerns due to increased cancer risks. Hence, dechlorination is often used to minimize gaseous chlorine concentration in the environment. Dechlorination requires use of many more chemicals that are toxic themselves. What is required is the development of processes that can be used to treat simultaneously both microbial and chemical contaminants. Although UV sources are known to work well in this path, developing pulsed UV is necessary to keep the UV dose to a minimum. Alternatively, pulsed corona, and electric discharges in water are some of the new promising processes that are being considered for the future of water treatment [43-49].

The pulsed high voltage discharges generated inside water, or on the surface initiate a variety of physical and chemical processes such as the formation of chemically active species like OH radicals and H_2O_2 along with O and H molecules, UV radiation, ozone formation and shockwaves. Through advanced oxidation, it is possible to break toxic chemicals without using any harsher chemical treatment. Unlike food treatment, a voltage of several tens of kilovolts is applied to the electrode system with a pulse repetition rate from 100 to 1500 pulses per second and pulse duration less than 10^{-6} s with water treatment. Ozone, UV-radiation, electric field and active particles are the factors that provide water disinfecting, and activate redox reactions, which transform the impurities to gas or solid insoluble forms.

Equally important are technologies to capture particulate contamination and oxides of nitrogen and sulfur. Use of pulsed power in energization of precipitators is constantly been improved, and new non-thermal processes are being developed for alleviation of air contamination [50-52]. As it is highly essential to control the power supplied to the precipitators and plasma reactors, almost all newer power supplies use solid-state switching devices.

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