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A Review of Pulsed Power Systems for Degrading Water Pollutants Ranging From Microorganisms to Organic Compounds

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ABSTRACT Water quality improvement and collecting safe water are two of the paramount concerns in today's world. Numerous water treatment and pollutant removal processes are introduced that vary with the type of pollutants. Among the proposed pollutant degradation methods, pulsed power is one of the effective methods that can be applied not only to degrade a wide range of contaminants but also to address the environmental issues associated with water treatment chemicals. The effectiveness of the pulsed power technology in water treatment was studied for a wide range of pollutants including microorganisms, nutrient pollution, emerging pollutants, and organic pollutants. This paper presents a review of pulsed power systems developed for organic and inorganic pollutants degradation in different water treatment applications. Also, it presents the effectiveness of several factors like the electrical characteristics of the pulse voltages and treatment time on degradation rates of different pollutants.

INDEX TERMS Water treatment, pulsed power systems, advanced oxidation method, decontamination.

I. INTRODUCTION

With respect to recent climate changes, efficient collection and storage of water are essential but not enough. The lack of efficient water treatment can result in environmental pollution and cause risks to human health. Drinking water shortage is one of the major threats to human lives throughout the world. Providing safe drinking water and maintaining a clean water environment are critical issues and need to be addressed properly using efficient and cost-effective treatment methods.

Compared to conventional water treatment technologies such as using chemical and antimicrobial additives, pulsed power technologies provide more benefits owing to several physical and chemical reactions occurring during the treatment process that makes these technologies more effective for the treatment of a wide range of pollutants [1]–[8]. In pulsed power systems, ultra-violet (UV) radiation, shock waves, charged particles, and free radicals can be generated due to plasma discharges. Water discharges and pulsed electric fields are mainly used for bacterial inactivation in water [9]–[11]. Electrical discharges in water and at water surface facilitate the destruction of the water pollutants [12], [13]. Generally, three electrical discharge systems have been used for water treatment: pulsed discharge plasma system, pulsed corona discharge system and dielectric barrier discharge system [14]. The UV radiation is generated by corona and arc discharge in water, where it can produce hydrogen peroxide and hydroxyl radicals and facilitate water decontamination process [15]–[19]. In conventional UV water treatment systems, low-pressure mercury lamps were used to emit germicidal radiation [20]. Low-pressure mercury lamps can generate several emission lines under 100-200 Pa pressure. Among these emission lines, only two of them are in the UV region with a wavelength of 185 and 254 nm and most of the emission lines are outside the microbial inactivation region. Compared to low-pressure mercury lamps, medium-pressure mercury UV lamps can produce several broad emission lines with higher light intensity under hundreds of kPa mercury pressure. Both low and medium pressure mercury lamps emit UV radiation continuously.

The ozonation process is widely used for drinking water and wastewater treatment [21], [22]. To improve ozone

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generation efficiency in the air, electrical discharges are usually used. The ozone generation can be influenced by several factors like input power, the discharge gap, the duration of applied voltage pulses and water vapor formed above the gas-liquid surface. With higher input power, a larger discharge gap, narrow high voltage pulses, and a thin layer of water vapor, ozone generation efficiency can be improved [23].

In the recent generation of the pulsed power systems, repetitive pulses with a moderate peak power are generated [24]. Conventional pulsed power generators (PPGs) generate high power pulses, hundreds kW (few hundred kV and few kA), with narrow pulse width (few ns). However, repetitive PPGs generate medium power pulses (few kW) with small duration (hundred μs- few ns) and a few hundred Hz to few kHz repetition frequencies. Repetitive PPGs benefit from high reliability, smaller size and lower maintenance compared to conventional PPGs [25]. Semiconductor switches and magnetic switches are usually used to improve the performance of PPGs [24], [26]–[28].

Pulsed discharge plasma is one of the effective methods introduced for water treatment. Generally, the proposed plasma water treatment methods can be classified as a remote plasma method, indirect plasma method, and direct plasma method. For the remote plasma method, the high-pressure plasma reactor is used to generate different hydroxyls and ozone to be injected into liquid samples [29]. Gas discharge lamps are usually utilized in indirect plasma methods to generate UV for water/liquid treatment. For direct plasma method, pulsed arc and corona discharges are usually occurred in contaminated water/liquid resulting in free radicals and ion generation [30]–[32].

In the pulsed corona systems, pulsed power supplies are utilized to generate high power pulses ($>$100 kW) with operating frequency of (100-1000 Hz), nanosecond order voltage rise time and short duration ($<\mu$s). In the pulsed arc discharged system, the operating frequency is lower than the corona system (10^{-2}-10^{-3} Hz) and the maximum amplitudes of the voltage and the current are $>$1 kV and $>$1 kA, respectively. A large energy capacitor is charged by a high voltage pulse with a microsecond rise time and is discharged directly into the water [33]. Among the electrical discharge systems proposed for water treatment, the pulsed corona discharge system in water demonstrated a better effect on the degradation of organic water pollutants [34]. Water surface discharge (WSD), in the form of pulse corona or streamer discharge on the water surface, has been proposed for effective microorganism decontamination, degradation of hazardous organic compounds, and treatment of harmful algal blooms [13], [35]. The advantage of this method is a simultaneous contact of the discharge plasma with gas and liquid molecules. Atmospheric WSD combines the gas phase discharge formed on the water surface with the liquid discharge, without requiring any additional supplementary gas [36]. WSD initiates several physical and chemical processes, resulting in intense EFs, UV emission, shock waves, and reactive radicals, ions, and molecular species in the air at the surface and in the water. Primary radicals or ions generated in the gas-liquid interface are injected into the water to react and form secondary molecular species, e.g., OH radicals, H_2O_2, and ozone, which are very efficient to degrade organic pollutants in water [36]–[39].

In a dielectric barrier discharge (DBD) system, the electrical discharges occur between two electrodes. One of these electrodes is covered by a dielectric material; i.e. water in water treatment application. An inelastic collision between free electrons is generated in the discharge gap due to an AC voltage, which consequently results in ionizing an ambient gas molecule and generating more free electrons. With more free electrons, an electron avalanche (streamer) will be produced that has high energy. Water pollutants will be degraded by free radicals and ions produced through plasma chemical reactions initiated by the energetic electrons [34].

The electric fields induce a transmembrane voltage on the biological cell that will result in electropermeabilization of the bacterial cell membrane and consequently decontamination of bacteria. For a spherical cell, the relationship between the induced transmembrane voltage and applied electric fields is given by Schwan's equation shown by Eq. 1 [40], [41].

$$\Delta\emptyset = 1.5ER\cos\theta \tag{1}$$

where $\Delta\emptyset$ is the induced transmembrane voltage, E is the applied electric field, R is the radius of the cell and θ is the polar angle between the charged surface in respect to the center of the cell.

In this paper, several pulsed power water treatment systems are reviewed and compared for the treatment of water contaminated with a wide range of pollutants including microorganisms and organic compounds. The rest of this paper is organized as follows: The pulsed power technology is introduced in section II. Several pulsed power systems developed for microorganism degradation are presented in section III. In section IV, organic compounds degradation methods developed based on pulsed power technology are discussed. Dye decomposition techniques, persistent organic pollutants, and pharmaceutical compounds degradation methods are presented in sections V, VI, and VII, respectively. Section VIII presents a few more pulsed power wastewater treatment methods developed for the degradation of compounds that are not listed in the aforementioned sections such as calcium carbonate, NO and N-dimethyl-p-nitrosoaniline. Finally, a conclusion is drawn in section IX.

II. PULSED POWER TECHNOLOGY

The technology of accumulating energy on capacitors and inductors over a relatively long period of time and releasing it over a very short period of time is known as pulsed power technology. Compared to multilevel converters by which the stored energy on DC link capacitors is released over multiple steps and generate staircase pulses [42], in the pulsed power system, the released energy is usually in the form of high-power unipolar or bipolar pulses [43]. A typical high-power unipolar pulse generated by a pulsed power system is

shown in Fig. 1. Although the power of the generated pulses is very high, around a few GW, their energy is very low, around a few J. In addition to the amplitude of the generated pulses, other electrical characteristics of the pulses like repetition rate, rise time, pulse duration, and the number of pulses play critical roles in the pulsed power applications [44], [45]. This is an emerging technology used for a wide range of applications including defense, food processing, liquid treatment, surfactant infection, bacteria inactivation, material processing and plasma medicine [24], [46]–[48].

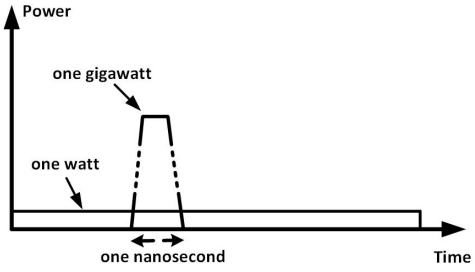

FIGURE 1. A typical high-power pulse generated by a pulsed power system.

When the generated pulses are applied to liquid and gas samples, plasma is produced that consists of charged and neutral particles like electrons, excited species, and ions. Generally, two different types of plasma are usually generated, thermal and non-thermal plasma. The thermal plasma is used for nuclear fusion and welding applications. However, non-thermal plasma is usually used for biomedical and environmental applications and includes plasma jets, corona discharges and dielectric barrier discharges (DBDs). The non-thermal plasma is based on chemical and physical reactions and results in biologicals effects and production of some biocidal agents such as electric fields (EFs), reactive chemical species, ultraviolet radiation (UV), heat and shock waves [46], [49]. The EFs are generated when high voltage pulses with short duration are applied across two electrodes placed on both sides of the sample. The pulsed EF showed great potential to be applied as an effective method for industrial and bioelectric applications such as food pasteurization and medical electroporation treatments [24], [46]. Several reactive species like OH radicals, ozone, and hydrogen peroxide can be formed in gas-liquid phases in a treatment system when plasma discharges are applied [50], [51]. With plasmas occurring in the gas phase above the liquid surface, the reactive species are formed, penetrated and dissolved into the liquid and facilitate the chemical and biocidal processes. However, with the plasma discharges generated in the liquid phase, physical processes like EFs, shock waves and UV highly contribute to the biocidal process in addition to chemical effects. The high oxidizing properties of these reactive species make them potential candidates for facilitating the decontamination/treatment processes.

The UV radiation is produced by the gas phase and underwater plasmas. The UV radiation with less than 300 nm wavelength was found to be an effective process for germicidal actions [18], [52]. The intensity of the UV produced from high voltage and high current arc discharges in water was found to be of the order 1 MW/cm^2 that is strong enough to inactivate most of the microorganisms in water [46]. Depending on the plasma energy, the thermal effects can be significant or moderate. For instance, for surface treatment of heat-sensitive materials, low energy plasma is used however for electrosurgery applications, high energy plasma and moderate thermal effects are more desirable. A portion of the underwater energy discharges converts to the shock wave formed in water. Shock waves have been used in several applications not only for bacteria inactivation but also for kidney stone disintegration, bone and tissue healing and pain treatment [46].

The shape of utilized electrodes and the electrical characteristics of the pulses (such as frequency, the amplitude of the voltage and pulse width) can affect the plasma phenomena which happens in the system. Plasma jets are highly used in biomedical applications because of their capability in extending the plasma to most regions, even the ones that are not confined by electrodes and dielectrics. For corona discharges, point-to-point, point-to-plane, and concentric rod-to-cylinder electrodes are usually used that lead to forming a sharp non-uniform field near one or both electrodes. Corona discharges occur when the localized field near electrodes is stronger than in the rest of the gap between the electrodes. DBD discharges can be achieved over a wide range of frequency (50 Hz- Radio Frequency) using two electrodes that at least one of them is covered by dielectric layers. A charge accumulates on the dielectric when a high voltage sinusoidal signal is applied to the electrodes and that results in generating a large number of micro discharges that are beneficial for biomedical and industrial applications like surface sterilization [46].

III. MICROORGANISMS DEGRADATION

Pulsed power systems were found to be an effective treatment method not only for industrial wastewaters but also for hospital and residential wastewaters. Non-thermal plasma is one of the effective methods introduced for microorganism inactivation and water disinfection and decontamination [53]–[55].

A. E. coli INACTIVATION

Escherichia coli (E. coli) is one of the most harmful bacteria that is widely found in wastewaters. Several treatment methods have been proposed for (E. coli) inactivation like using mercury lamps, a pulsed xenon flashlamp, and non-thermal plasma. In comparison with mercury lamps, pulsed xenon flashlamp can emit several strong UV radiations under 50-100 kPa xenon pressure and pulsed conditions. A pulsed xenon flashlamp was used in [56] to provide high energy UV radiation with a broadband emission spectrum for Escherichia coli (E. coli) inactivation. A pulsed power source was utilized to produce high power pulses to drive the flashlamp. In this system, a 40 μF capacitor was first charged to store 20 J of energy and then discharged through

the flashlamp within 30 μs. Driving the flashlamp by several narrow pulses resulted in generating high energy UV radiation. The experimental results revealed that the germicidal efficiency of pulsed UV radiation is a function of the wavelength. The short duration and high-power characteristics of the pulsed UV sources make them potential candidates for rapid disinfection. A needle to plate electrode configuration was used in [15] for E. coli inactivation in aqueous solutions using UV radiations generated by corona discharges. The initial amount of viable E. coli bacteria was 10^5 CFU/ml and the volume of bacteria solution was 1600 ml. Potassium ferrioxalate actinometry was utilized for quantitative analysis of ultraviolet radiation. In this regard, several solutions with different conductivities (100-500 μS/cm) and pH values (2.8-3) were prepared. The needle electrode was made of tungsten wire and energized by high voltage pulses with the amplitude ranging from 17-29 kV and repetitive frequency of 0-100 Hz. The experimental results showed that increasing solution conductivity and the applied voltage resulted in UV radiation with stronger intensity. On the other hand, for higher solution conductivity the yield H_2O_2 decreased because of increasing photolysis of H_2O_2. The E. coli concentration decreased by four orders of magnitude after 15 min treatment using 23 kV pulsed voltage with 50 Hz repetition frequency.

Pulsed electric fields were also introduced as an effective means to degrade bacteria like E. coli [57]. The results presented in [57] showed that for the applied pulses with 60 ns, 300 ns and 2 μs duration, 164 kV/cm, 107 kV/cm and 66 kV/cm electric fields were required respectively for one log reduction of E. coli in 0.1 cm^3 of tap water. As it is discussed in [58], the strong electric field and narrow high voltage pulses are the most effective factors for bacteria decontamination.

A continuous treatment chamber including two high voltage and ground electrodes was designed for E. coli and Bacillus subtilis (B-subtilis) spore inactivation [58]. The designed treatment chamber is shown in Fig. 2. The volume of the treatment area in the chamber was 2.8 – 4.75 ml and the flow rate was 0.25 L/min. The effects of all critical factors including electric field intensity, pulse shape and duration, treatment time and temperature on E. coli and B-subtilis spores inactivation were studied. The initial concentration of the bacteria strains was 10^5-10^6 CFU. In the designed system, magnetic pulse compressor was utilized to increase the repetition rates of the high voltage pulses. For E. coli inactivation, 19 kV pulses with a duration of 200 ns full-width at half-maximum (FWHM) and 110 kV/cm electric field were applied that resulted in 3-4 log reduction in E. coli viability. Also, it was shown that 1.5 mm change in the electrode gap led to one log reduction in E. coli viability. The investigation on the relationship between pulse repetition rate and E. coli viability revealed that with higher repetition rate lower E. coli viability was achieved. For instance, with 45 pulses, E. coli viability decreased by one order of magnitude whereas, with 70 pulses, it reduced by four orders of the magnitude. In addition to pulse repetition rate, higher electric field, 110 kV/cm resulted in higher inactivation rate, 4 logs reduction in E. coli viability. One log reduction achieved for B-subtilis spores using 110 kV/cm electric field and 19 kV pulses with a duration of 200 ns full-width at half-maximum.

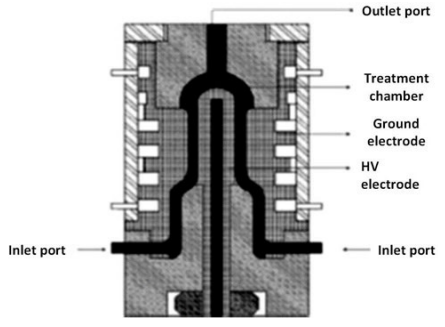

FIGURE 2. Coaxial treatment chamber for E. coli and B-subtilis spores inactivation [58].

An E. coli inactivation system was developed in [59] using a three-phase discharge plasma reactor that was energized by a bipolar pulsed power supply. The developed three-phase reactor consisted of a high voltage electrode that was not in direct contact with water and a ground electrode. The utilized pulsed power supply has a capability to generate pulses with the amplitude between 0-100 kV (peak-peak) and with a repetition frequency of 1-200 Hz, the rise time of 40-100 ns, and pulse width of 500-1000 ns. In this study, it was shown that the strong electric field, formed active species and the pH of the solution are more critical factors for facilitating the inactivation process whereas solution conductivity is less effective. The experimental results revealed that for 250 ml solution contaminated with E. coli with a concentration of 10^6 CFU/ml it took about 5 min to achieve 98.5% inactivation efficiency using 50 kV pulses with 50 Hz repetition frequency and with 910 μS/cm solution conductivity. Also, it was illustrated that under the same electrical conditions, the inactivation efficiency reached about 96% when the pH of the solution was 7.26 (alkaline solution).

The effect of nanosecond pulsed electric field on the E. coli inactivation was studied in [60]. For conducted tests, E. coli bacteria (with an initial concentration of 10^{12}) was added to one liter of salty water with a conductivity of 0.02 S/m. The water solution was injected into a treatment chamber equipped with two stainless steel electrodes placed in parallel. The diameter of both electrodes was 15mm and they were separated by a 2mm gap. The utilized pulse generator generated pulses with 20 kV amplitude, 1 Hz frequency, 60 ns duration, and 20 ns rise time to excite the high voltage electrode. The number of pulses was changed between 100 and 500. It was shown that the nanosecond PEFs could affect the E. coli membrane permeability and reduce the viable E. coli resulting in one log reduction using 500 pulses.

Pulsed dielectric barrier discharge (DBD) reactor is used in numerous applications to produce non-thermal plasma

for water purification. In [61], a wire-cylindrical discharge plasma reactor was developed to inactivate E. coli in 250 ml water solution. Glass pellets and air bubbling have been utilized to facilitate the water treatment process and increase the treatment efficiency by generating strong UV radiation and more chemically active species like O_3, H_2O_2, OH and O. The inactivation efficiency increased to 99.98% after 25 min of treatment using bipolar pulsed DBD at 40 kV and 50 Hz and air bubbling with an airflow rate of 0.75m^3/h. Fig. 3 shows the schematic diagram of the developed system for E. coli treatment.

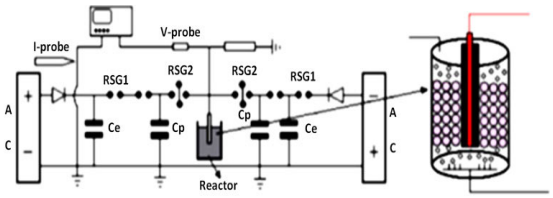

FIGURE 3. Schematic diagram of the developed system for E. coli treatment [61].

The electric field, shock waves, ozone and active species caused by streamer discharges generated in water massively contribute to the decomposition of pollutants and microorganisms. Having said that, the streamer discharge method is known as one of the effective methods proposed for water decontamination.

A water disinfection system was developed in [62] to treat 50 ml water sample contaminated with E. coli bacteria with a concentration of 10^7 cells/ml using a pulsed streamer discharge system. As shown in Fig. 4, a needle plate is used for streamer discharge. A discharge free transformer, a high voltage diode and rotating spark gap switch were used to generate a high voltage AC signal, high voltage DC signal and high voltage square pulses, respectively. The experimental results revealed that the treatment time, applied voltages and alkalinity are the most effective factors that can change the treatment efficiency. Also, it was shown that the treatment time decreased significantly, when the number of pulses, the amplitude of the applied voltage and the operating frequency were increased. For 7 log reduction of E. coli, 23 kV pulses with a frequency of 25 Hz, 0.4 μs rise time and 17 ms duration were applied that resulted in 100% E. coli reduction after 10 min of treatment.

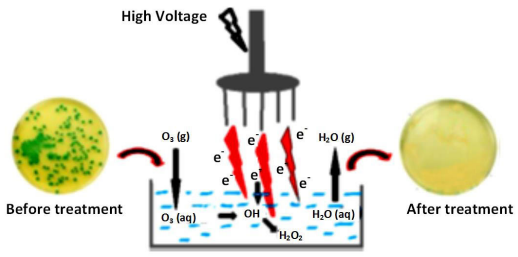

FIGURE 4. Pulsed power system with needle plate configuration for water disinfection [62].

A corona discharge reactor including multiple tungsten electrodes with a needle plane configuration was utilized in [63] for E. coli degradation that is shown in Fig. 5. In this system, a transformer is used to increase the input voltage that is then rectified through a high voltage diode. Square pulses are generated using a rotating spark gap, and its switching speed determines the duration of generated pulses. The plasma treatment caused deformations of bacteria membrane and E. coli cell devastation. The results illustrated that all E. coli cells were totally degraded (7-log reduction) after 6 min treatment applying 23 kV pulses with a frequency of 25 Hz.

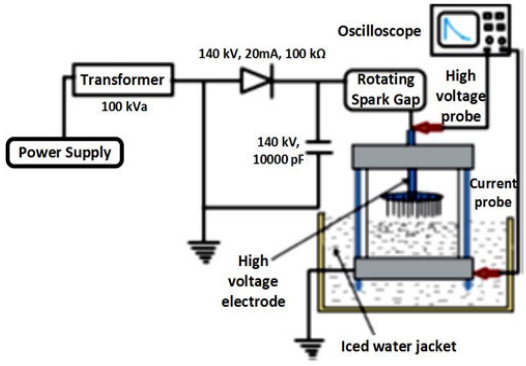

FIGURE 5. E. coli treatment system with multiple electrode reactor with a needle plane configuration [63].

A pulsed corona supply was designed including a tungsten wire electrode to degrade E. coli and Bacillus subtilis bacteria in 10 ml water and vegetative state respectively [64]. The wire reactor generated corona discharges when it is excited by 120 kV pulses with 0.1 Hz frequency and a duration of 600 ns. After eight and fifteen corona discharges E. coli concentration dropped by about three and four orders of the initial concentration, respectively.

To decrease B. subtilis concentration in the vegetative state down to 10^{-4} of its initial concentration, 30 corona discharges were required. In addition, a plane-to-plane electrode was utilized to generate a homogeneous electric field for E. coli decontamination. Compared to the pulsed water corona discharge method, the degradation efficiency achieved by using the pulsed electric field was lower.

A gliding arc reactor consisting of two stainless steel electrodes shown in Fig. 6 were used to generate arc discharges that resulted in producing low power non-thermal plasma used for E. coli colonies inactivation [65]. A portable flyback pulsed power supply was utilized. The amplitude and frequency of the generated pulses were 20V and 250Hz, respectively. The water sample was sprayed through low power pulsed gliding arc discharge to enhance E. coli inactivation. Classical colony counting method was used to quantify the inactivated E. coli colonies. The results showed that after 2 min treatment, E. coli colonies were reduced by

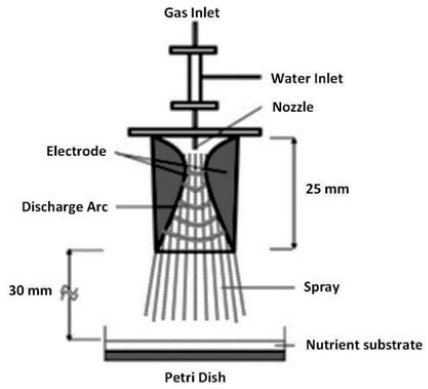

FIGURE 6. Gliding arc reactor developed for E. coli inactivation [65].

4 logarithmic units by spraying the water sample through plasma using air/ argon as carrier gases. Also, it was illustrated that when bacteria were in adherent phase, increasing the gas flow rate led to H_2O_2 reaction and penetration enhancement and consequently higher E. coli inactivation rate.

A multiple-needle-cylinder reactor was designed to generate unstable pulse arc discharges for treatment of 300 ml deionized water contaminated with E. coli [66]. In the developed system, a microsecond pulse generator was used to generate 20 kV pulses with 100 Hz frequency and energy of 0.2 J/pulse. The duration of the main pulse was 150 ns. Several experimental tests have been conducted to study the effect of electrode gap distance, different electrical parameters and solution characteristics on E. coli inactivation efficiency. The experimental results showed that with 5 mm electrode gap distance, the plasma energy density of 8 J/ml, water conductivity less than 50 μS/cm and 3.5 L/min air bubbling flow, 100% E. coli decontamination rate was achieved after 5 min. In addition, it was shown that among the examined parameters, energy density has the highest impact on the E. coli inactivation rate.

A wastewater treatment system was developed in [67] to disinfect a water solution (10 ml) contaminated with E. coli and Enterococcus faecalis (E- faecalis) as a gram-negative and gram-positive bacteria, respectively. Spark discharge plasma was generated using two needle electrodes. High voltage pulses with an amplitude of 10 kV and a frequency of 30 Hz were generated to excite the high voltage electrode. Electric field and H_2O_2 molecules were produced through plasma reaction process and effectively contributed to E. coli and E. faecalis inactivation. Compared to these two factors, pH was not an effective factor for bacteria inactivation. The initial concentration of E. coli and E. faecalis cell was 10^8 CFU/ml. The complete inactivation of E. faecalis was achieved after 12 min of treatment; however, longer treatment time (15 min) was required for E. coli inactivation because of the complex structure of gram-negative bacteria. The results showed that as the treatment time goes by, the nitrate and nitrite concentration increased that could be a side effect of the proposed method.

B. LEGIONELLA PNEUMOPHILA MICROBES INACTIVATION

Legionella pneumophila is commonly found in natural and manufactured water systems that may cause lung infections and pneumonia especially in aged people with weak immune systems. Treatment of the Legionnaire's disease can be a time-consuming process and patients may require intensive care. Therefore, the prevention of these diseases is necessary and can be accomplished by disinfecting the water systems.

Two disinfection methods were proposed in [68] for decontamination of Legionella pneumophila microbes. For pulsed corona disinfection method, high voltage pulses with an amplitude of +80 kV, 20 Hz frequency, 140 ns pulse duration, and 20 ns rise time were generated by a Marx-Bank pulse generator to produce plasma at the electrode/liquid interface using a tungsten high voltage electrode. This method resulted in 100% bacterial decontamination and no Legionella colonies were found after 12.5 min of the treatment. The pulsed electric field was also introduced as an effective disinfection method for this application. In this system, the electric field was generated along the wire by applying -80 kV pulses with a frequency of 20 Hz and 240 ns duration. Compared to plasma treatment, all Legionella colonies were not totally removed after 25 min of treatment time and the decontamination rate was decreased (the viable cell population was 2.54 CFU/ml) by PEF treatment. In comparison to the pulsed electric field, for the same input energy, pulsed corona plasma was found to be more efficient decontamination method.

C. PSEUDOMONAS BACTERIA

A colony of microorganisms that are attached to surfaces like piping is known as biofilms that can cause problems in human health and ecosystems. Pseudomonas bacteria is a common bacteria that can be found in water, soil, and plants [69]. Biofilm formation of Pseudomonas bacteria on the surfaces of drinking water reservoirs and pipes can be a major threat to human health and effective disinfection methods are required for inactivation and removal of the microbial biofilms. Different studies showed that pulsed power systems can effectively affect this type of bacteria and can be a potential replacement for chemical disinfection methods used for hospital wastewater treatment.

1) PSEUDOMONAS FLUORESCENS AND SPORES OF BACILLUS CEREUS

Two pulsed electric field and pulsed corona discharge systems have been designed in [70] for treatment of liquids and air contaminated with microorganisms. The effects of pulsed electric fields and corona discharges on inactivation of Pseudomonas fluorescens (gram-negative bacterium) and spores of Bacillus cereus (gram-positive bacterium) have been studied. The generated pulses had these specifications: 100 kV amplitude, 10 ns rise time, 150 ns duration, the repetition rate of 1000 pps. The experimental results showed

that with 70 kV/cm electric fields generated in liquid, for one log reduction of Pseudomonas fluorescens and Bacillus cereus, 85 kJ and 500 kJ energy should be delivered per liter of these solutions, respectively. Compared to pulsed electric fields, corona discharges occurring in a liquid medium was a more efficient process by which lower energy (25 kJ/L) was required for one log reduction of both gram-positive and gram-negative bacteria. For corona discharges occurring in the air, the efficiency of 2 J/L per log reduction was reported.

2) PSEUDOMONAS PUTIDA

A pulsed electric field treatment system was developed in [71] to treat the hospital wastewater sample consisting of pathogenic and antibiotic-resistant bacteria. The Pseudomonas putida with a concentration of 10^8 CFU/ml was suspended in a water solution and used as a reference bacterium. The developed system generated pulses with an amplitude of 20 kV, a duration of 600 ns and frequency of 0.3 Hz to energize the electroporation cuvettes with the volume of 400 μL that were filled with wastewater samples. This system could reduce the Pseudomonas putida population by 3.6 logs of CFU using 10 pulses without increasing genotoxicity in hospital wastewater or generating genotoxic byproducts in tap water. The maximum bacteria reduction achieved was 6 log of CFU using 120-200 pulses.

D. MICROBIAL PATHOGENS DECONTAMINATION

A high voltage pulsed-plasma gas-discharge system was developed in [72] to inactivate the microbial pathogens in the poultry wash water. The proposed system could affect a wide range of microbial pathogens in poultry wash water including E. coli, Campylobacter jejuni, Campylobacter coli, Listeria monocytogenes, Salmonella enterica serovar Enteritidis and S. enterica serovar Typhimurium, all with an initial concentration of 10^8 CFU/ml. The developed system that is shown in Fig. 7 included one stainless steel grounded electrode, a coaxial high voltage electrode and eight pulse forming lines to generate high voltage pulses. The charging voltage of the pulse forming line was 23.5 kV and pulse rate was 124 pps and the energy per pulse was 3.7 J. The outcomes of the experimental results showed that with this treatment system, the populations of microbial pathogens were reduced significantly ($\leq$ 8 log CFU/ml) within 30 s treatment time at 4 OC.

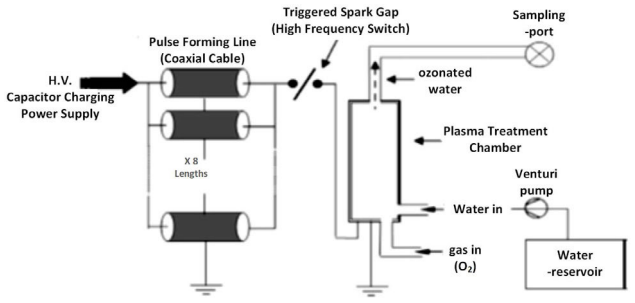

FIGURE 7. Pulsed-plasma gas-discharge system for poultry wash water microbial pathogens inactivation [72].

E. CYANOBACTERIA CELLS DESTRUCTION

A pulsed streamer discharge system was developed in [73] to degrade the M. aeruginosa cells. M. aeruginosa is one type of cyanobacteria. As illustrated in Fig. 8, a grounded cylinder electrode and a stainless needle discharge electrode were used to generate streamer-like discharge. The needle discharge electrode was excited by 160 kV pulses with 2 μs duration generated by a Blumlein-type pulse forming network. The pulsed power generator consists of a DC source, a pulse transformer, a spark gap switch, and 15 LC ladder stages. The discharge current through the discharge chamber and the applied energy were 500 A and 83J/pulse, respectively. It was shown that shockwave and discharge current were two effective factors for cyanobacteria cells destruction and M. aeruginosa sediment was formed and settled at the bottom of the chamber after 2 hours of treatment time.

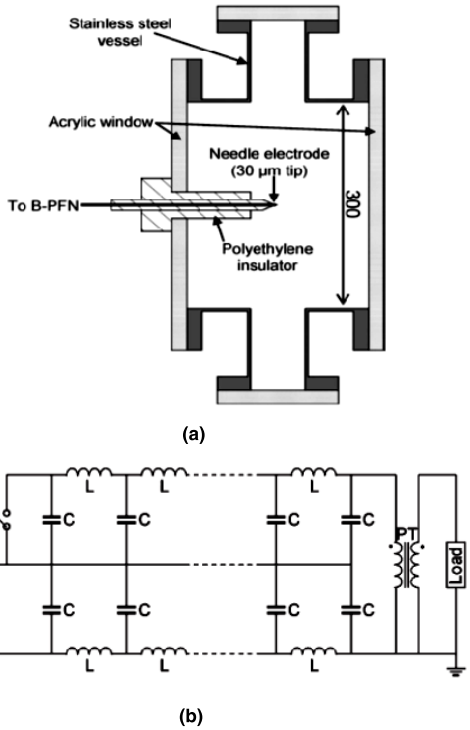

FIGURE 8. Pulsed streamer discharged system (a) discharge chamber, (b) pulsed power generator [73].

An underwater plasma discharge device shown in Fig. 9 was developed in [74] using 12 2mm-tungsten capillary electrodes inserted into a reactor to degrade 10-50 μm microorganisms (Tetraselmis suecica, Nauplius, Thalassiosira sp., Skeletonema sp., Biddulpia sp.) and heterotrophic, E. coli, intestinal enterococci and Vibrio cholera O1, O139 bacteria in ship's ballast water. The electrodes were energized by 1.2 kV pulses with a frequency of 10 kHz and a pulse width of 5 μs. The flow rate and the volume of the reactor were 5 ton/h and 1.59 L, respectively. The number of surviving

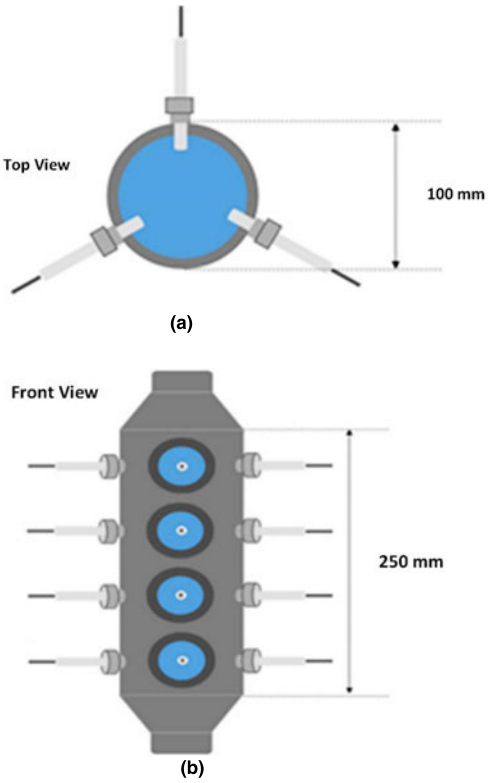

FIGURE 9. Underwater plasma discharge device consists of 12 2mm-tungsten capillary electrodes [74].

bacteria was measured in the treated ballast water on day 0 and day 5. After plasma treatment, the concentration of 10-50 μm algae microorganisms decreased significantly from 1613 cells/ml to 2 cells/ml and from 139 cells/ml to 5 cells/ml on days 0 and 5, respectively. In addition, the developed system could degrade the involved heterotrophic bacteria, E. coli, and Intestinal enterococci bacteria. The initial size of its colony was 591 cells/ml and it dropped to 189 cells/100ml after pulsed power treatment on day 0 and to 43 cells/ml on day 5. In addition, no E. coli and Intestinal enterococci bacteria cells were detected after pulsed power treatment on day 5.

IV. ORGANIC COMPOUNDS DEGRADATION

High voltage pulse discharge in water is one of the effective methods introduced for organic compounds decomposition due to strong UV radiation, intense shock waves and chemically active species generated by plasma discharges in water. For the efficient and effective plasma generation, the applied high voltage pulses should have a fast rise time and narrow width. The formation of active species is highly affected by the structure of the plasma/discharge reactors [75].

Several plasma reactors have been designed for efficient toxic organic compounds decontamination, which are mainly based on pulsed corona discharges, dielectric barrier discharges, streamer, and spark discharges and ozone [76]. The corona discharge in the gas phase would result in more free radicals and free electrons generated through corona discharge process that can facilitate the pollutants degradation [63]. Pulsed corona discharge reactors are the most used reactors for water treatment systems. These reactors are usually made of stainless steel and designed in the form of a needle, multiple needle plate, and wire. High voltage pulses with short rise time and duration are usually generated to energize the reactors. The highest decontamination efficiency would be achieved by spraying a water solution into plasma in the gas phase [76].

A. PHENOL DECOMPOSITION

A pulsed high voltage process is one of the effective methods that has been used for hazardous chemical wastes treatment. Active hydroxyl radicals, oxygen radicals, and ozone are generated through non-thermal plasma generation process and can affect the organic chemical compounds and degrades them [37], [77]. Several pulsed power systems mainly corona discharge systems were developed to decompose phenol in water solutions.

An aqueous phenol decomposition method was proposed in [37] using a high voltage pulsed streamer discharge formed in the gas phase above the water surface. Among the utilized reactors, a ring-shaped ground electrode played an effective role in phenol decomposition compared to straight and semicircular electrodes. High voltage pulses, 25 kV with a repetition frequency of 100 Hz were applied to treat 200 ml distilled water contaminated with 50 ppm phenol. The phenol decomposition rate was studied in different enveloping gases including oxygen, air, and argon. It was shown that argon was the most effective gas that could enhance the phenol decomposition rate up to 80% over 5-20 mm distances between the needle electrode tip and the water surface. Although using argon as an enveloping gas resulted in higher phenol decomposition rate, the change in argon flow did not affect the phenol decomposition rate. However, with higher oxygen flow rate, lower phenol decomposition rate was achieved. Also, it was shown that after 60 min treatment time with 1 L/min oxygen flow rate, the decomposition rates achieved with water surface plasma, streamer discharges, and corona discharges were around 60%, 25%, and 15%, respectively.

Two stainless steel and tungsten electrodes have been used as a grounded and high voltage electrodes to decompose two organic compounds, phenol, and sodium formate both with 1mM concentration, by discharging inside bubbles in water [77]. Both electrodes immersed in the water solution with a volume of 15 ml. A pulsed power generator has been developed to excite the tungsten electrode. The amplitude and repetition rate of the generated pulses were 20 kV and 250 pps, respectively. For the water solution contaminated with only sodium formate, 30 min of treatment time was required for 100% TOC removal rate; however, for the phenol solution, the TOC removal rate was 17% after 30 min.

A nanosecond pulsed power generator was developed to treat a 500 ml surfactant aqueous solution [78]. Nonylphenol ethoxylate is one of the persistent surfactant pollutants.

Several treatment methods have been proposed for surfactant treatment. Among the proposed methods, pulsed power is introduced as the most effective treatment method due to the large production of hydroxyl radicals caused by UV and shockwaves generated by pulsed discharges. Fig. 10 shows a schematic diagram of the developed pulsed power system. In this system, a highly pressurized gas gap switch is used to generate a high voltage pulse with a sharp rising time. When the inner wire electrode was energized by nanosecond pulsed power, streamer discharges occurred between the inner wire electrode, the flowing solution, and the outer electrode. The discharge plasma generated between two inner and outer electrodes affected the flowing solution. Active species were generated by electric discharges and UV and then immersed in the solution. The surfactant solution concentration was 400 ppm. High voltage pulses with the amplitude of 39 kV and duration of 1.5 ns were applied to the high voltage reactor. It was shown that 100% decomposition rate was achieved after 20 min treatment.

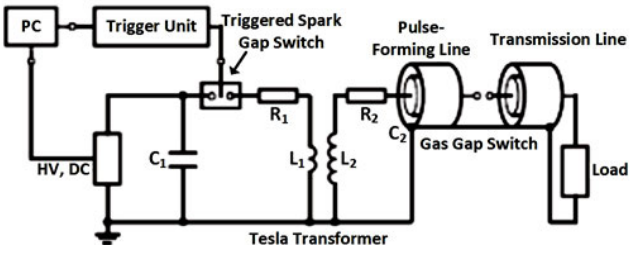

FIGURE 10. Schematic diagram of the streamer discharge system developed for surfactant treatment [78].

A pulse generator was developed in [79] to generate pulses with an amplitude of 40 kV, 10 Hz repetition frequency and 50 ns duration to excite the utilized reactor. The reactor created pulsed corona discharges above the water to degrade the phenol in water solution. The developed corona above water system is shown in Fig. 11. The initial concentration of the phenol was 1 mM. The phenol removal rate achieved by adding hydrogen peroxide (1mM) was 91%. However, by adding iron (III) sulfate with 1 mM concentration and butanol with a concentration of 1 mM, the removal rate changed to 69% and 40%, respectively.

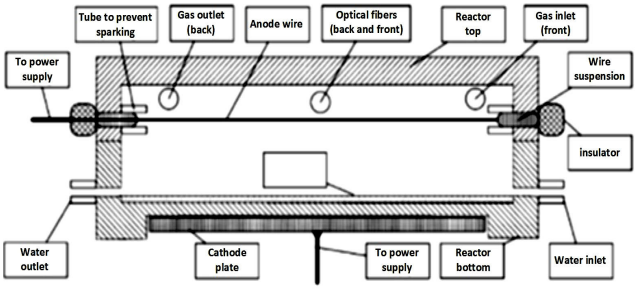

FIGURE 11. Phenol removal system using corona above water reactor [79].

To degrade the organic compounds specifically phenol in a water solution, a treatment system shown in Fig. 12 has been developed in [80]. Pulsed high voltage discharges including streamer corona discharge and spark discharge have been generated using needle-plate electrode and a pulse generator. To generate streamer corona discharge, the needle electrode was energized by 17.5 kV pulses with 5 μs duration while for spark discharge generation the needle electrode was excited by 20 kV pulses with a duration of 5 μs. The pulse repetition rate for streamer corona discharge was 30 pps while for spark discharge the repetition rate was 2.54 pps. The phenol in the water solution was totally degraded after 75 min of treatment time by streamer corona discharge. However, longer treatment time (100 min) was required for complete degradation of the phenol when the spark discharge was applied.

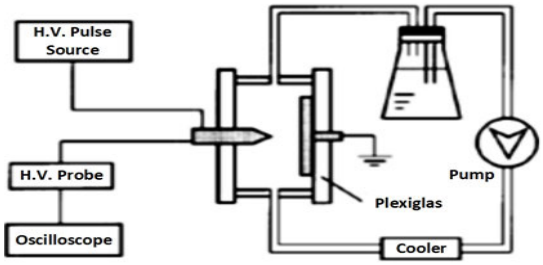

FIGURE 12. Phenol degradation system using a high voltage pulse generator and needle-plate electrode [80].

Pulsed-streamer corona discharge was used in [81] to form a non-thermal plasma for phenol degradation (with 50 ppm initial concentration) in aqueous solution. The corona discharge also resulted in generating active species including hydroxyl radical, hydrogen peroxide and ozone. These active species were beneficial for achieving effective degradation process. The schematic diagram of the developed system is shown in Fig. 13. A point-to-plane electrode with a diameter of 46 mm and a length of 32 mm was utilized. High voltage pulses with adjustable amplitudes ranging from 0 to 30 kV, fast-rising time (several tens of ns) and 48 pps repetition rate were applied to the reactor to generate a corona discharge. For 20 kV applied pulse voltage, the complete phenol removal was achieved after 12.7 min of residence time. It was shown

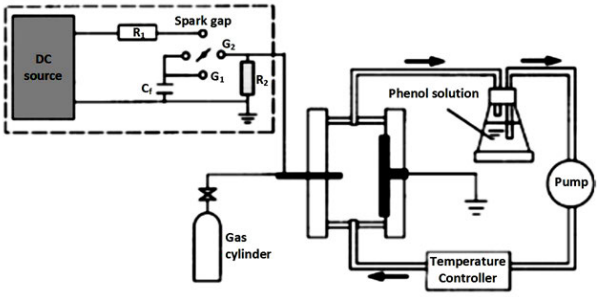

FIGURE 13. Pulsed-streamer corona system for phenol degradation [81].

that with 17 kV pulses, the treatment time could be decreased to 12 min and 10.6 min using argon gas bubbling and oxygen gas bubbling, respectively. In addition, the total organic carbon removal rate was reported as 86% and 83% after 22 min with and without oxygen gas bubbling using 17.5 kV pulses.

Two reactors, corona above water and aerosol reactors have been used in [82] for aqueous and gaseous streams treatment and facilitate biodegradation in wastewaters. The combination of pulsed corona and catalyst resulted in 99% of the degradation of phenol. A high-power pulse generator was designed to generate 60 kV pulses with a frequency of up to 500 Hz, the rise time of 15 ns and 100 ns duration. It was shown that corona above water reactor presented higher efficiency for phenol degradation compared to other techniques for which both electrodes of the reactors are placed in the water. For the purpose of water treatment with a flow rate of 200 L/h, four corona above water modules have been developed which can handle 210 A. A phenol reduction of 33% was achieved after one pass and at a yield of 200 g/kWh using four-module treatment system with 7.2 W input power applied to four modules. However, the phenol reduction rate of 99% was achieved after three passes and at a yield of 18 g/kWh using aerosol reactor with four nozzles and 360 W input power.

Degradation of phenol in aqueous solution was conducted in [83] using a pulsed discharge plasma reactor. Oxygen and argon were used as additive gases to facilitate the phenol degradation process. Compared to argon, oxygen addition resulted in a wider and stronger streamer discharge. The presented results revealed that the degradation efficiency was improved by increasing the input voltage, the energy delivered to the reaction system, solution pH and gas bubbling rate. Compared to these factors, the solution conductivity presented little effect on phenol degradation efficiency. It took about 120 min to completely degrade phenol with an initial concentration of 50 ppm in 200ml solution with a conductivity of 100 μS/cm and 7.6 pH, using 30 kV input pulsed voltage with 100 ml/min oxygen flow rate.

In [84], a pulsed corona discharge reactor consisted of a needle-point electrode and a planar ground electrode was used to degrade phenol as an organic compound in a water solution. The initial phenol concentration and the pH in water solution were 100 ppm and 5, respectively. As shown in Fig. 14, the high voltage electrode is submerged in the water solution and supplied by 45 kV pulsed voltages with the frequency of 60 Hz. Two ground electrodes were used for tests, a stainless steel ground electrode and a reticulated vitreous carbon with the macroscopically porous surface. The stainless steel ground electrode was placed 3-5 mm above the water surface to form discharges in the liquid phase, gas-liquid phase and gas phase. Such a configuration produces a non-thermal plasma discharge in the gas phase and pulsed streamer corona discharge in the liquid phase, generating hydrogen peroxide and hydroxyl radicals in the liquid phase and ozone in the gas phase. The combination of these phenomena led to the formation of more reactive species in the gas and liquid phases, improving the phenol removal rate. The removal rate of phenol was 35% after 60 min treatment when the stainless steel ground electrode was placed in the gas phase contains pure oxygen and potassium chloride salt was added to the solution. Higher removal rate (97.5%) was achieved when the test conditions were almost the same and just potassium chloride salt was replaced by ferrous sulfate. The phenol removal rate reached 97% after 30 min of corona treatment using reticulated vitreous carbon electrode. This improvement is mainly due to the larger amount of ozone generated because of using a vitreous carbon electrode.

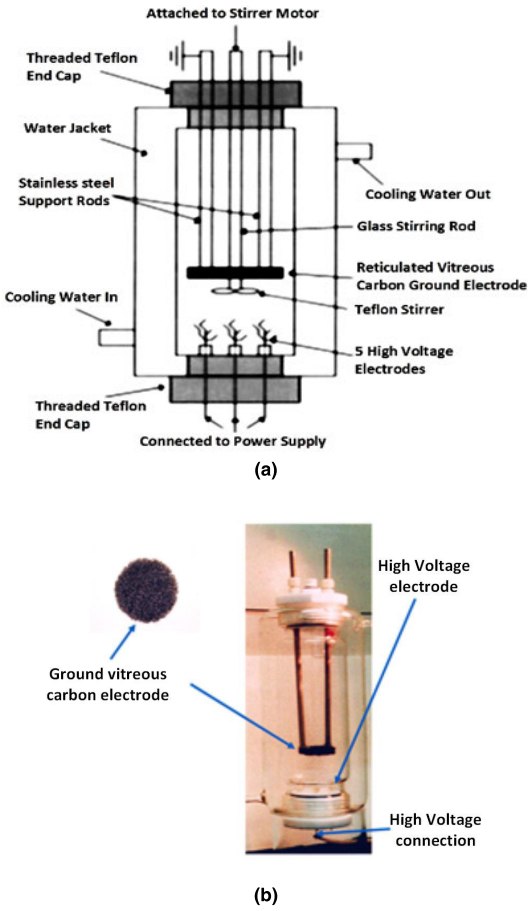

FIGURE 14. Phenol degradation system with needle-point electrodes and (a) a stainless steel ground electrode, (b) vitreous carbon ground electrode [84].

B. ACID DECOMPOSITION

A multiple pin-plane corona discharge reactor was developed in [85] to degrade 2, 4 dichlorophenoxyacetic acid (2, 4-D) with an initial concentration of 10mg/l. The developed prototype is the same as the one proposed in [62]. It was shown that the oxidation rate of organic compounds is proportional to the applied pulse voltage and frequency, it means for faster degradation rate, pulses with higher voltage and frequency are required. As it is addressed in [62], 92% removal rate was achieved after 10 min of treatment time with 15 kV pulses

and a frequency of 25 Hz. However, 6 min treatment time was required to completely remove 2, 4-D pollutants when 25 kV pulses with 25 Hz frequency were applied.

A corona discharge water treatment system was developed in [86] for organic compounds (phenol, acetic acid, and Rhodamine B) decomposition. Two stainless steel wire and plate electrodes were utilized. The plate electrode was grounded and submerged in a water solution and the wire electrode was placed above the water surface to create a corona discharge in the gas phase. The wire electrode was supplied by positive and negative high voltage DC signals in a range of 17-20 kV. The phenol degradation rate was increased when a negative high voltage signal was used for wire electrode excitation. Further enhancement in degradation rate was observed in the experimental results when corona discharge was generated in O_2 and CO_2 mixture in the gas phase. Also, it was shown that 50% concentration for O_2 was the optimum concertation by which a high degradation rate over a short treatment time was achieved. As it is shown in experimental results, 17 mm was the optimum gap between two electrodes at which higher degradation rate was achieved compared to 14 mm and 20 mm gaps. For 100 ml of a water solution contaminated with phenol with a concentration of 50 g/m^3, the maximum degradation rate of aqueous phenol (C6H5OH) (>99%) was achieved after 1-hour treatment when 16.7 kV DC voltage was applied and the ratio of CO2 and O2 was 3/7.

As it is addressed in [87], advanced oxidation methods like UV and ozonation failed to effectively remove perfluoroalkyl acids due to strong carbon-fluorine bond. To address this issue, a plasma-based water treatment system including a laminar jet with bubbling (LJB) reactor was developed in [87] to remove perfluorooctanoic acid (PFOA) in a water solution. High removal rate and high removal efficiency have been targeted through the experimental tests. To achieve a high removal rate, the discharge voltage and energy were set at 25 kV and 0.63 J respectively and the repetition frequency was 120 Hz. However, for high removal efficiency, the discharge voltage, energy, and frequency were decreased to 16 kV, 0.13 J, and 20 Hz, respectively. The achieved results revealed that for 20 μM concentration of PFOA dissolved in 1.4 L of deionized water, 30 min treatment time was required for 90% removal of PFOA when a high-power input signal (76.5 W) was applied (high removal rate). For the same PFOA concentration and the sample volume, only 25% of PFOA was removed when the input power was 4.1 W (high removal efficiency).

A plasma discharge system with nine-hole electrode system was developed in [88] to decompose acetic acid with an initial concentration of 10 ppm in a water solution. In this system, the utilized dielectric spacer has nine holes that allow for nine parallel oxygen discharges. Compared to other water pollutants, acetic acid is more persistent and has a better reaction with Hydroxyl radicals (OH) than ozone. To generate OH, several methods have been proposed like pulsed streamer discharges, pulsed/DC discharges in bubbles floating in the water and pulse corona discharges over the water surface. Compared to the single-hole electrode system, the decomposition efficiency of acetic acid was improved using a nine-hole electrode system. In the developed system shown in Fig. 15, the high voltage pulses discharged in the bubbles generated in the water solution to facilitate the decomposition rate of the acetic acid. It was shown that with higher solution conductivity, discharge input power, and repetition frequency, more OH radicals were generated resulted in higher decomposition rate. However, to avoid the high quenching rate of OH radicals, the input discharge power should be decreased. The idea of using the nine-hole electrode found to be an effective solution for generating more OH radicals and decreasing the OH radicals quenching rate. The generated high voltage pulses had an amplitude of 8 kV, a frequency of 1 kHz, the rise time of 100 ns and a duration of 200 ns. The largest reduction in total organic carbon (TOC) concentration (5.5 ppm) was achieved using oxygen as a discharge gas after 20 min of treatment time and the maximum decomposition rate was 19.8 μg/min.

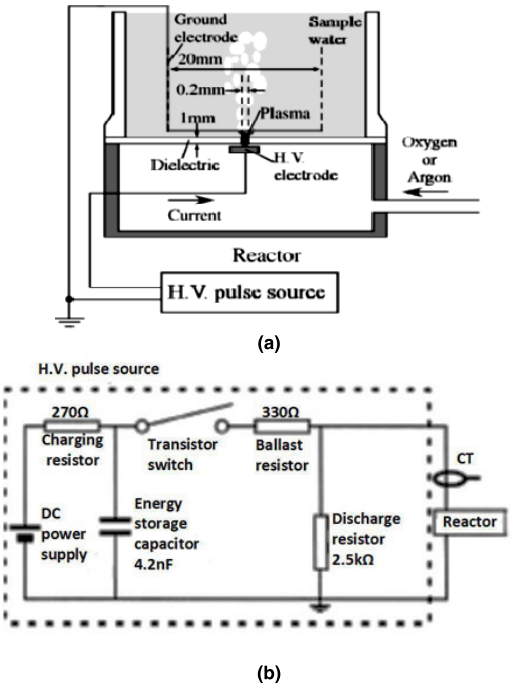

FIGURE 15. A plasma discharge system with nine-hole electrode system (a) the system block diagram (b) high voltage pulse supply [89].

V. DYE DECOMPOSITION

So many Industrial settings such as textile manufacturers and die users generate wastewater with high concentrations of toxic organic pollutants. Conventional treatment technologies such as chemical processing, biological treatment, and advanced filtration systems are not always suitable options for such pollutants degradation due to the possibility of generating secondary pollutants and high maintenance costs. Therefore, an advanced, cost-effective and efficient technique is required for the decomposition of dye wastewater [90], [91].

A. INDIGO CARMINE DECOMPOSITION

Two pulsed DBD reactors were developed to treat the indigo carmine as a waste agent for dye wastewater treatment [90]. The first one was an extendable reactor with five electrodes covered with quartz tubes and the second one was an array reactor. A pulsed power supply was developed consisting of two transformers and a rectifier to charge a capacitor. A hydrogen thyristor was used to control the capacitor discharge. The maximum amplitude achieved for discharge pulse was 17 kV and its duration and repetition rate were 130 ns and 130 pps, respectively. The experimental results showed a 99% decolouration efficiency after 10 min treatment, an 83% unsaturated bond decomposition rate after 60 min treatment and a 74% chemical oxygen demand degradation rate. The developed dye wastewater degradation system is shown in Fig. 16.

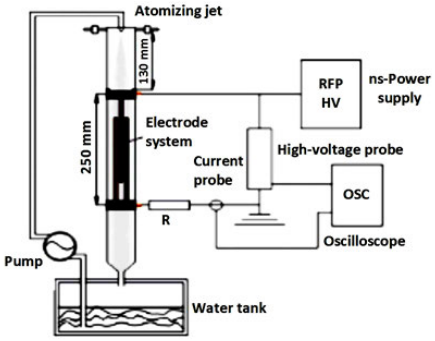

FIGURE 16. Dye wastewater degradation system using pulsed DBD reactor [90].

A pulsed corona discharge reactor consisting of a cylindrical electrode and a discharge wire was used in [91] to decompose dye in water solution. Fig. 17 presents the pulsed power generator with a pulsed corona reactor developed for dye decomposition in water solution.

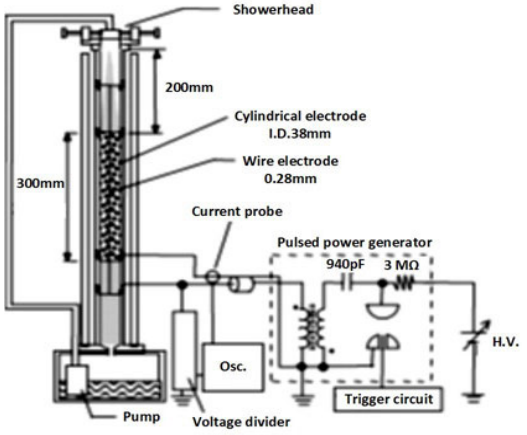

FIGURE 17. Pulsed corona discharge system for dye decomposition [91].

In this system, a pulsed power generator (PPG) generated a 25 kV pulse with a duration of 70 ns, a repetition rate of 100 pps and 50 ns rise time. To study the performance of the developed system, at first water solution of indigo carmine was sprayed into the corona reactor then discharge power was injected into the reactor. The experimental results revealed that for indigo carmine, 1 min treatment with 8.6 W discharge power is required for the chromogenic bond decomposition while unsaturated bond was decomposed (complete decomposition) after 60 min of treatment time with the same discharge power. Also, it was shown that for the same discharge power, the decomposition rate of the unsaturated bond was more influenced by a larger number of pulses than higher charging voltages.

A coaxial dielectric barrier discharge (DBD) system was applied in [92] to degrade indigo carmine solution with 250 mg/l initial concentration. As it was addressed in [80], pulsed DBD method usually produces ozone and UV radiations and is more efficient and effective decontamination method compared to Fenton oxidation, ozone treatment, and bioremediation method. Fig. 18 presents the schematic diagram of the developed coaxial DBD system. The experimental results showed that with higher discharge voltage, more oxidation products such as H_2O_2 and O_3 were produced. Also, it was shown that the indigo carmine solution was totally degraded after 10 min treatment using 25 kV discharge voltage with 200 Hz frequency.

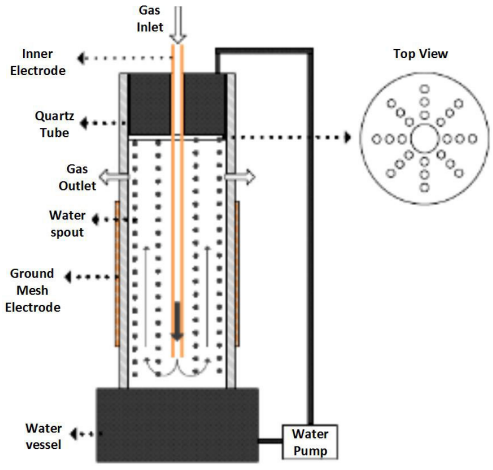

FIGURE 18. Schematic diagram of the coaxial DBD system for indigo carmine degradation [92].

In [93], a seven-electrode reactor was designed to treat indigo carmine solutions consisting of 15.4 mg/l of potassium indigo trisulfonate, 1.33 g/L of phosphoric acid and 1 g/L of sodium dihydrogen phosphate. Increasing the number of electrodes resulted in effective treatment within a shorter time compared to a one-electrode reactor. The experimental results showed that for the developed seven-electrode reactor, the concentration of the generated ozone is 1.3 mg/l that is about 1.6 times greater than the ozone concentration achieved by the one-electrode reactor. The seven-electrode reactor was excited by high voltage pulses with an amplitude of about 25 kV and a repetition rate of 500 pps. The discharge power

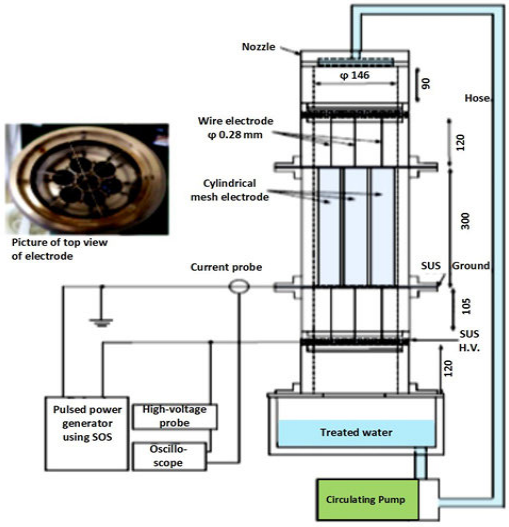

FIGURE 19. Indigo carmine decomposition system with seven-electrode reactor [93].

per pulse was 87 mJ. Fig. 19 shows the treatment system with the seven-electrode reactor. The treatment time for 100% reduction of indigo carmine with 20 mg/l initial concentration was 40 s using the seven-electrode reactor; however, with one-electrode reactor with 12 mJ discharge power per pulse, the treatment time was 300 s for 100% reduction of indigo carmine.

An indigo carmine decoloration method was proposed in [89] by spraying water solution droplets into a pulsed streamer discharger in the air phase. The investigation on the solution samples revealed that by spraying water droplets into the discharge area reduced the time (0.57 times shorter) required for indigo carmine decoloration compared to flowing the water film on the chamber wall. It was also shown that the decoloration process was faster near the cylindrical electrode than near the wire electrode. The sample water volume was 1L and its concentration was 20 mg/l. High voltage pulses with an amplitude of 28.2 kV and frequency of 100 pps were applied and the discharge current was 111 A. Experimental results showed that by spraying the water solution into discharge area near the cylindrical electrode, where more radicals were available, the achieved decoloration rate was 100% after 2 min treatment.

An indigo carmine decolorization was conducted in [94] using a coaxial cylinder reactor comprised of a wire electrode (inner electrode) and a cylinder electrode (outer electrode). The wire electrode was supplied by nanosecond pulses to produce streamer discharges in the gas phase close to water solution surface. For the experimental test, 500 ml water solution including indigo carmine with a concentration of 20 mg/l was prepared. Fig. 20 presents the developed treatment system. The experimental results showed that the decolorization ratio could be improved utilizing higher charging voltage and pulse repetition rate. For instance, 100% decolorization rate was achieved after 12 min treatment

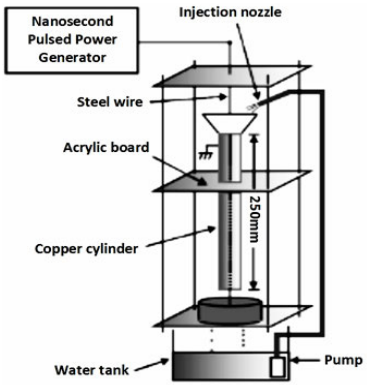

FIGURE 20. Developed coaxial cylinder reactor for indigo carmine decolorization [94].

with 2.78 kV charging voltage and 50 pps pulse repetition rate while with the same charging voltage and 10 pps pulse repetition, 100% decolorization rate was achieved after 20 min treatment. Also, it was shown that during 4 min treatment and with 50 pps pulse repetition rate, the decolorization ratio was about 65% when the applied charging voltage was 2.78 kV that increased to about 78% with 3.2 kV charging voltage. Although increasing the pulse repetition rate resulted in higher decolorization ratio, the decolorization efficiency dropped at higher pulse repletion rate. In addition, it was shown that using ozone did not result in higher decolorization efficiency as compared to using the discharge reactor.

A coaxial electrode consisting of a stainless wire and a grounded cylindrical stainless mesh as shown in Fig. 21 was developed to generate streamer discharge in the air for indigo carmine decomposition [95]. One liter water solution composed of indigo carmine with a concentration of 20 mg/l dissolved in purified water was prepared for the experimental test. The solution droplets were formed using a nozzle and sprayed into the acrylic cylinder for treatment. The charging voltage was 13.5 kV and the pulse repetition rate was 1000 pps. In the experimental tests, several pulses with

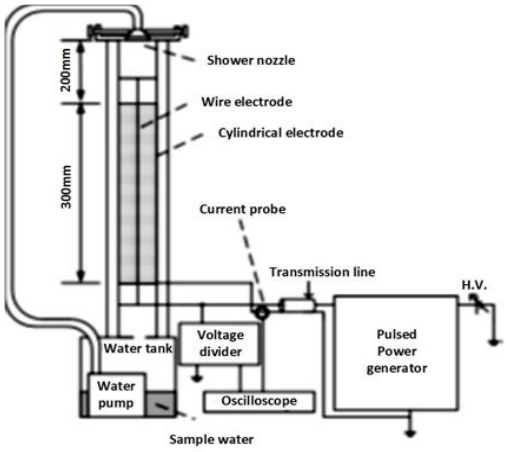

FIGURE 21. Indigo carmine decomposition using a coaxial electrode and pulse power generator [95].

different durations (60, 80, 100, 120 and 140 ns) were applied. As it was shown in the experimental results, the treatment time decreased using wider pulses up to 100 ns but beyond this value ($\geq$100 ns) the treatment time increased because the decomposition ratio decreased. Therefore, with 13.5 kV charging voltage with 100 ns duration and 1000 pps repetition rate, the highest efficiency was achieved for both the generator and the indigo carmine treatment. The composition ratio reached about 95% after 60 min treatment time. Also, it was illustrated that higher resistance of the pulse power generator resulted in higher discharge power and efficiency for the generator and treatment.

A point-to-plane electrode configuration was used in [36], [38] to treat orange II and indigo carmine organic dyes with WSD. A high voltage needle electrode was placed in air and a plate ground was immersed in water [36] as shown in Fig. 22. Indigo carmine solution with 30 mg/l concentration in deionized water was used. The authors first analyzed the effects of pulse voltage amplitudes on the chemical process induced by the WSD. They applied 9.1 to 21.6 kV of about 2 μs duration pulses at 500 Hz pulse repetition rate. The complete decoloration of the indigo carmine solution was achieved after 7.5 minutes with 16.5 kV pulse amplitude. They reported 0.4 to 0.65 g/kWh energy efficiency for 40% decoloration for voltage amplitudes from 9.1 to 21.6 kV [36].

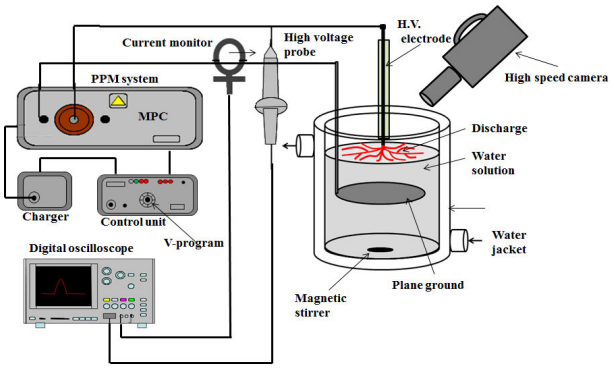

FIGURE 22. Water surface discharge for decomposing indigo carmine used in [36].

B. AZO DYE DECOMPOSITION

The textile industry is one of the main industrial wastewater generators. They are using numerous dyes with different chemical structures. One of the highly used dyes is azo dye with several bonds of hydroxyl, nitrogen, and amines [96]. Several pulsed power systems have been used for azo dye degradation in industrial wastewaters. A plasma discharge system was used in [96] for the degradation of Acid black 52 (AB52) with a concentration of 1 mM. The developed system contained two tungsten electrodes, one was immersed in the water solution (cathode) and the other one was placed on the gas phase, 5mm above the water solution surface (anode). A high voltage DC signal with an amplitude of 1 kV was applied to the anode. The DC electrical discharge (plasma discharge) occurred in the gas phase above the water solution resulted in generating active species like NO, O_2^+ and Na and reactive oxygen species that diffused into the water. The interactions between the generated active species and the water samples led to dye molecule breaking and color decomposition. The initial volume of the prepared water solution was 100ml. The experimental results revealed that by adding ferrous sulfate ($FeSO_4$) to the water sample, a higher degradation rate achieved due to larger HO generated. The degradation rate achieved after 60 min of treatment was 96% by adding $FeSO_4$; however, the degradation rate was 30 % after 90 min of treatment without Fe.

A multi-needle-to-plate reactor was utilized for azo dye decoloration [97]. In this pulsed-corona discharge system, the reactor was supplied by high voltage pulses with $<$100 ns rise time, the maximum amplitude of 50 kV, adjustable repetition frequency ranging between 0-200 Hz and $<$500 ns duration. These pulses were generated using an adjustable DC power supply, adjustable trim capacitance, 2 nF storage capacitor and rotating spark gap switch as shown in Fig. 23. The experimental results showed that for higher pulse voltage amplitude and frequency, the decoloration rate increased significantly. For 400 ml solution contains azo dye with a concentration of 10 mg/l with pH of 6.4, the decoloration rate reached about 58% after 60 min treatment when 30 kV pulses with 50 Hz frequency were applied. The decoloration rate increased to 94.8% after 60 min treatment with 30 kV pulses and 75 Hz repetition frequency whereas the decoloration rate was about 18% after the same treatment time and with 30 kV pulses and repetition frequency of 25 Hz. Also, it was shown that with 30 kV pulses at a repetition frequency of 50 Hz and three different pH levels (4, 6.4, 10), the maximum decoloration rate (86.7 %) was achieved at pH $=$ 4 after 60 min treatment. In addition, it was shown that the gas bubbling rate could significantly affect organic pollutant degradation. With more accelerating electrons originated from discharge electrode in the multi-needle-to-plate reactor and higher gas bubbling rate, higher ionization rate will be achieved between accelerating electrons and gas molecules that results in higher decoloration rate.

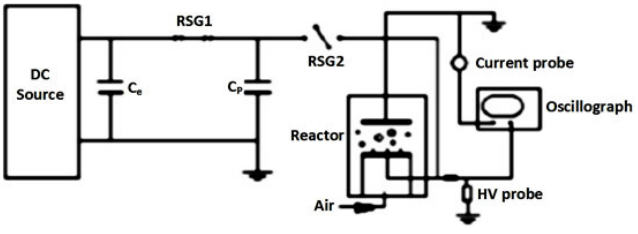

FIGURE 23. Azo dye decoloration system using multi-needle-to-plate reactor [97].

Sunset yellow is a member of the azo dye family that is widely used in different industries ranging from food to the textile industry. Several advanced oxidation methods like Fenton process, photochemistry, zonation, and wet oxidation

have been proposed to treat the sunset yellow wastewater. The main drawback of most of these methods is producing dye wastewater sludge [98], [99]. High voltage pulsed electric discharge is one of the effective advanced oxidation processes for sunset yellow wastewater decoloration [100]. Zho et al. designed a point-to-plane electrode system and a copper mesh-plate discharge system in [100] to degrade sunset yellow with an initial concentration of 50 mg/l in 1L solution. Zho et al. studied the change in the degradation rate with respect to the variation of pH, reactor configuration, discharge type and bubbling gas type. The utilized pulsed power supply generated 30 kV pulses with 66.7 Hz repetition frequency, 20 μs duration and very sharp rising time. Two different types of discharge systems were developed, a hybrid gas-liquid discharge system for which the plate electrode was immersed in solution and a hybrid series discharge system with a plate electrode above the solution surface. Compared to hybrid gas-liquid discharge system, the series discharge system could generate more ozone that resulted in the production of more OH and H_2O_2. Also, it was shown that by adding the oxygen gas bubbling, Fe^{2+} (forming Fenton reaction) and using copper mesh plate the degradation process can be improved. Among different pH values, pH $= 1$ had the highest impact on the sunset yellow degradation process. The degradation efficiency was nearly 100% after 120 min when the copper mesh plate and oxygen gas bubbling were used.

Amaranth is one of the synthetic azo dyes used in dye and food industries and cannot be degraded by conventional water treatment techniques. A three-phase discharge plasma reactor was developed in [101] to remove amaranth from a water solution. The amaranth removal rate was investigated under different physical and electrical conditions. An aqueous solution contaminated with amaranth with a concentration of 24 mg/l dye was used for experimental tests. The dye solution was injected into the reactor first and then the formed gas bubbles were added to the reactor to facilitate dye contamination and active species formation leading to decontamination efficiency improvement. The number of active species formed during the decontamination process was related to the gas flow rate. For high gas flow rate, more air bubbles and consequently more active species were formed. In addition to the gas flow rate, it was shown that the decolorization rate was highly influenced by the applied pulse voltage, pulse duration, and repetition frequency, pH and solution conductivity. To avoid temperature rise in plasma channels, the input voltage was increased to a certain level, 50 kV and beyond this level, the decoloration rate decreased. At high repetition frequency, higher energy density was achieved and the more energy delivered to the sample resulted in generating more active species and higher dye removal efficiency. The solution pH and initial conductivity had contrary effects on the decoloration rate. For a solution with high pH, the decoloration rate decreased whereas, with high initial conductivity, the decoloration rate increased. The decolorization rate achieved after 30 min of treatment time was 81.24% using 50 kV voltage pulses with 50 Hz frequency.

Wang et al. developed a pulsed discharge plasma system suitable for organic dye decoloration [102]. The developed system is shown in Fig. 24 was equipped with a DC power supply, a rotating spark-gap switch and two capacitors, one as storage and the other one as a trimming capacitor. A multi-needle-to-plate electrode was used to generate a plasma discharge in the gas-liquid phase. Acid orange 7 (AO7) with an initial concentration of 20 mg/l was used as an organic dye sample. High voltage pulses with an amplitude of 16 kV, 18 kV and 20 kV and a frequency of 50 Hz were generated. In order to facilitate the decoloration process and improve the efficiency of the system, air bubbles with different flow rates (0 L/min, 2 L/min and 4 L/min) and activated carbon were added to the solution. The experimental results showed that with 20 kV, 50 Hz pulses and a flow rate of 4 L/min, the decoloration rate was 76.7% after 120 min of treatment time without adding activated carbon. However, by adding activated carbon, this rate increased to 96.1% after the same treatment time.

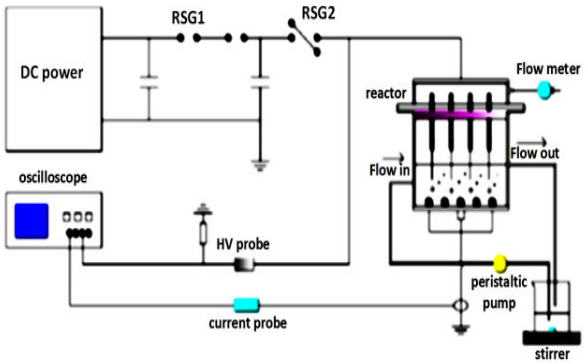

FIGURE 24. A pulsed plasma discharge system developed for acid orange 7 decoloration [102].

A plasma discharge system was used in [103] for degradation of Acid Orange 142 (AO142) dye in 100 ml water solution. The developed plasma discharge system composed of a DC power supply and a pin-to-plate reactor that consists of two electrodes with a 5 mm gap between them. A high voltage electrode was made of different materials (aluminum, steel, and copper) and excited by 12.5 kV DC voltage and a stainless steel ground plate electrode immersed in the water solution. The initial concentration of AO142 was 20ppm. Among different materials used for high voltage electrode, steel resulted in higher degradation efficiency that was mainly due to the catalytic effect of Fe^{2+} generated through steel electrode corrosion during the treatment process and diffused into the solution. Generally, it was shown that addition of an iron catalyst to the plasma process resulted in larger degradation efficiency. Also, it was shown that at lower pH level (pH 3, acidic condition), Fe^{2+} is more stable and more reactive oxygen species were generated due to Fenton's reaction that resulted in higher dye degradation rate. The maximum decoloration efficiency (95.05%) was achieved at constant

pH = 3 after 20 min of treatment using high voltage steel electrode and Fe^{2+} with initial concentration of 0.9 mM.

C. ORGANIC DYE DECOLOURATION

In [104], three pulsed plasma discharges have been investigated for organic dyes degradation in contaminated water using two needle-to-plane electrodes. Fig. 25 presents the developed continuous dye degradation system. A high-power supply is used to generate high voltage pulses with 20 kV amplitude and 25 Hz frequency. Three discharge modes include streamer, spark and spark-streamer modes. Hydroxyl radicals, UV light radiation and shock waves were generated through decoloration process. In comparison between these three discharge modes, it was demonstrated that during streamer discharge treatment dye removal by hydroxyl radicals was dominant process whereas, during spark and spark-streamer discharge treatments, physical effects like UV radiation and shock waves are more dominant factors for the efficient dye removal process. The prepared solution included Rhodamine B (basic dye), Methyl Orange (acid dye), and Chicago Sky Blue (direct dye) all with a concentration of 0.01 g/L. it was shown that spark-streamer mode enhanced the decoloration process resulted in a 95% decoloration rate for 300 ml of the solution after 100 min of treatment.

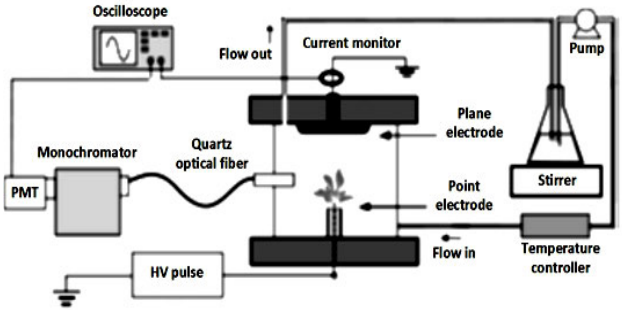

FIGURE 25. Organic dyes (Rhodamine B, Methyl Orange, and Chicago Sky Blue) degradation system [104].

A high-frequency bipolar pulse power system is shown in Fig. 26 that was designed in [105] to generate pulsed electrical plasma discharge using tungsten wire-to-wire metal electrodes. For the experimental tests, 250 ml of demineralized water was mixed with an organic dye Fluorescein-4-isothiocyanate and the conductivity of the solution was 500 μS/cm. The amplitude and frequency of the applied bipolar pulses were 900 V and 5 kHz, respectively. T_{on} time (pulse duration) was 20 μs and T_{off} (time interval between pulses) time was 200 μs. It was shown that with adding air bubbles, it is possible to achieve electrical discharge in solution at low discharge voltage and liquid conductivity. Also, T_{off} time was found to be the most effective parameter for optimization and energy efficiency improvement in the developed system.

A glow discharge plasma wastewater treatment method was proposed in [106] that was found to be more cost effective and efficient for organic pollutants treatment as compared to the corona discharge method. Two different electrode

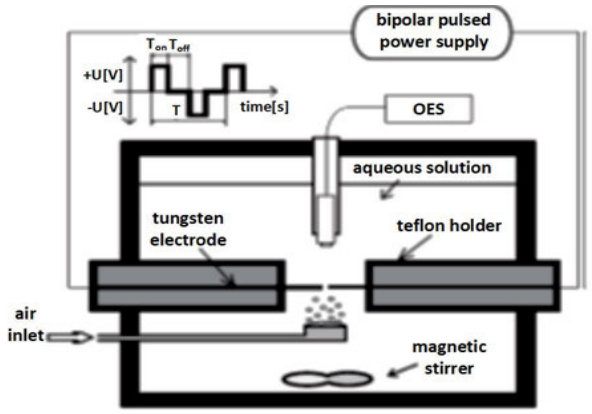

FIGURE 26. Fluorescein-4-isothiocyanate decomposition using a bipolar pulse power system with wire-to-wire tungsten electrodes [105].

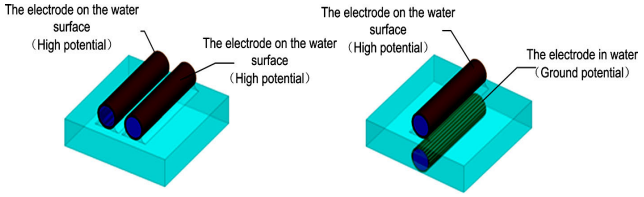

FIGURE 27. Electrode configuration for the glow discharge plasma system (a) parallel configuration and (b) perpendicular configuration [106].

configurations have been designed, parallel and perpendicular configurations as shown in Fig. 27. For the parallel model, two high voltage electrodes were placed on the surface of the water solution in parallel. For the perpendicular model, the ground electrode immersed in a water solution and the high voltage electrode was placed on the surface of the water perpendicular to the ground electrode. Methyl orange and azobenzene both with a concentration of 10 mg/l were used as organic pollutants. The volume of the water solution was 50 ml. The discharge voltage amplitude was 6 kV and its frequency was 20 kHz. The distance between electrodes and the immersion depth were changed to study their effects on the generated magnetic fields and the electric field area. The applied electric field strength was varied by changing the distance between the electrodes and/or immersion depth. For instance, increasing the immersion depth to 1.5mm reduced the electric field to 5.55 MV/m compared to 7.4 MV/m for a 0.5 mm immersion depth. Also, increasing the distance between two parallel electrodes from 3mm to 5mm decreased the electric field from 7.56 MV/m to 6.62 MV/m. After 15 min of treatment with 4mm horizontal distance between parallel electrodes, methyl orange, and azobenzene decoloration rates were 93% and 85%, respectively.

D. METHYLENE DEGRADATION

A methylene blue degradation approach was presented in [107] using a pulse power system as shown in Fig. 28. In this system, the cylindrical container was filled with contaminated water. The distance between the water level and the tip

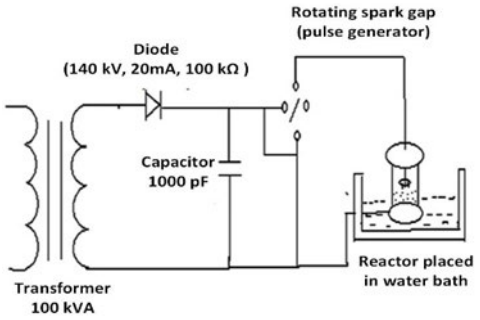

FIGURE 28. Pulse power system for methylene degradation using needle plate reactor [107].

of the electrode was adjusted for optimum reactive oxygen species formation. High voltage pulses with an amplitude of 23 kV and a frequency of 25 Hz were generated to degrade methylene with a concentration of 50 mg/l. As shown in experimental results, methylene compounds were completely degraded after 10 min treatment. This paper also showed that high alkalinity and the natural organic matter had a negative effect on methylene degradation efficiency and decreased the rate of reactive oxygen species formation while acidic pH enhances reactive oxygen species formation.

To decolorize methylene blue in distilled water, pulsed corona discharge and ozonation systems were combined in [108]. The developed system consisted of a 40 kV DC source, a needle –plate reactor, a rotating spark gap switch, an O_2 cylinder and an O_3 generator as shown in Fig. 29. The experimental results revealed that the methylene blue with a concentration of 13.25 mg/l in 20 ml sample was decolorized after 120 min when high voltage pulsed corona discharges (40 kV) with 60 Hz repetition frequency have been applied. By adding O_2 bubbling with a flow rate of 10 ml/min, the decoloration time decreased to 25 min and it could be even reduced to 8 min if bubbling of O_2 contained 1500 μ mol O_3/l. Also, it was shown that for pulsed corona discharge with the bubbling of O_2 contained 1500 μmol O_3/l, the energy efficiency was improved by 15 times as compared to pulsed corona discharge with O_2 bubbling.

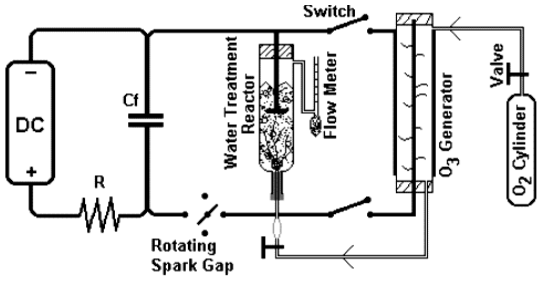

FIGURE 29. Methylene blue decoloration system using pulse corona discharge and ozonation [108].

A pulsed corona discharge reactor was used in [109] for methylene blue and phenol decomposition in water. The developed system consisted of a 40 kV DC source, a rotating spark gap switch operated at 60 Hz, Pyrex tube reactor fitted with needle-plate electrodes. Silica gel and alumina were used as effective plasma catalysts to facilitate methylene blue and phenol decomposition process. Fast-rising pulses, 50 ns with an amplitude of 40 kV with a repetition rate of 60 pulses/s have been applied to decompose methylene blue and phenol with initial concentrations of 13.25 mg/l and 25 mg/l, respectively. With the flow rate of 3.3 ml/min, the methylene blue concentration dropped to 3 mg/l using pulsed corona discharges in water and it was further reduced to 1.1 mg/l and 0.47 mg/l by adding α-alumina and γ-alumina, respectively. The combination of silica gel and corona discharges resulted in methylene blue with ultra-low concentration (below the detection limit) after more than 100 hours of treatment. For phenol decomposition, the flow rate was 3.3 ml/min and pulsed corona discharges resulted in 4 mg/l phenol reduction. Lower phenol concentrations, 9 mg/l, and 8 mg/l were achieved using ozone and silica gel respectively in addition to pulsed corona discharge. The addition of ozone and silica gel together with pulsed corona discharges resulted in 3.5 mg/l phenol residual. The best energy efficiency achieved for methylene blue and phenol decomposition using pulsed corona discharges, ozone, and silica gel simultaneously was 2.7×10^{-9} mol/J and 5.7×10^{-9} mol/J respectively with a flow rate of 10 ml/min for methylene blue solution and 3.3 ml/min for phenol solution.

VI. PERSISTENT ORGANIC POLLUTANTS

Persistent organic pollutants (POPs) are usually found in wastewaters and hardly can be degraded using conventional water treatment methods. However, nanosecond pulsed discharge plasma can be effectively applied for the degradation of this type of pollutants. A nanosecond pulsed discharged method is presented in [110] to continuously degrade POPs in 1L oil and gas industrial wastewater. To enhance the effectiveness of treatment, the wastewater was spraying to the gas phase region. As shown in Fig. 30, the developed continuous treatment system had a coaxial cylinder discharge reactor with a high voltage tungsten electrode and a stainless steel ground electrode. The amplitude of the generated nanosecond pulses was changed between 30 kV and 50 kV and the repetition rate was changed between 200 and 1000 pps. The flow rate of the treatment system was 205 L/min. The effectiveness of the decontamination process was evaluated by measuring the total organic carbon (TOC) in the organic compounds. The experimental results showed that there is a positive correlation between the discharge voltage and achieved TOC removal rate for a given number of pulses that means larger discharge voltages resulted in higher decontamination rates; however, at a certain voltage level, applying more pulses did not increase the decontamination rate. For instance, the TOC removal rate achieved at 40 kV and with 600 pps was higher than that achieved with 1000 pps. The maximum TOC removal rate was 35% after 3 hours of continuous treatment using 40 kV pulses with 600 pps.

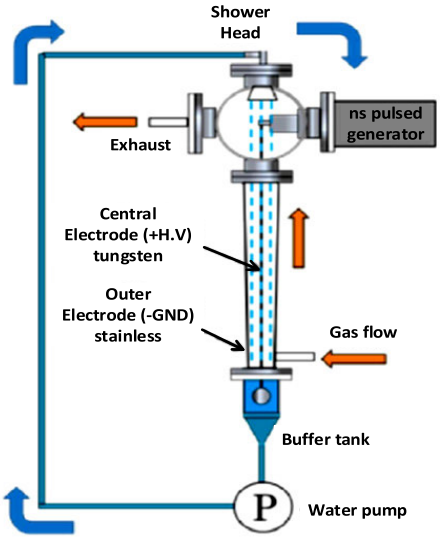

FIGURE 30. Nanosecond pulsed discharge plasma system for POPs degradation [110].

VII. PHARMACEUTICAL COMPOUNDS DEGRADATION

Several pulsed power treatment systems were developed to degrade single and mixed pharmaceutical compounds. Depends on the structure of the pollutants, treatment duration may vary. For instance, longer treatment is required for mixed pollutants compared to single pollutants [111].

A pulsed corona discharge system that is shown in Fig. 31 was developed in [98] for pharmaceutically active compounds (PACs) degradation such as diclofenac (DCF), carbamazepine (CBZ) and ciprofloxacin (CPF). The initial concentration of utilized PACs was 1 mg/l. In the developed system, a multiple-needle pulsed corona reactor was used to generate pulsed corona discharges. The high voltage electrode was excited by 25 kV pulses with a repetition frequency of 30 Hz. All DCF, CBZ, and CFP compounds were completely degraded after 4, 6 and 8 min treatment, respectively.

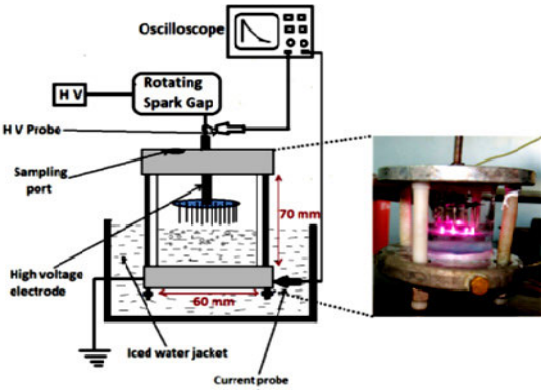

FIGURE 31. Pulsed corona discharged system for DCF, CBZ and CPF degradation [111].

A plasma generation system was developed in [112] using a helical resonator and a Pt/Ir electrode to degrade four popular pharmaceutical compounds including ampicillin, ibuprofen, fluoxetine, and propranolol. As shown in Fig. 32, a sinusoidal signal was generated and amplified to energize the helical resonator and excite the electrode. The fundamental frequency of the sinusoidal signal was adjusted according to the frequency of the resonator that was 1.65 MHz and the amplitude of the signal was kept at 71 V. The distance between the tip of the electrode and the water surface was fixed at 2mm. The initial concentration of all compounds except fluoxetine was 100 mg/l. Fluoxetine initial concentration was 25 mg/l. After 3 hours of plasma treatment, Ibuprofen and Ampicillin were the least and the most degraded compounds with 90.91% and 100% degradation rates, respectively. Fluoxetine and Propranolol were the second and third highly degraded compounds with a degradation rate of 99.66% and 99.64%, respectively.

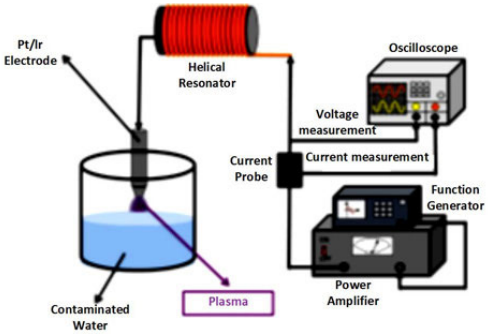

FIGURE 32. Plasma discharge system applied for degradation of ampicillin, ibuprofen, fluoxetine, and propranolol in water solutions [112].

A coaxial dielectric barrier discharge (DBD) reactor was used in [113] to degrade pentoxifylline with a concentration of 100 mg/l in 200 ml water solution. Two electrodes were utilized, the inner electrode was supplied by a high voltage and the outer one was grounded. The pentoxifylline solution was pumped from the reservoir and flowed on the surface of the inner electrode where it was exposed to the plasma discharge in pulsed mode. The developed setup is shown in Fig. 33.

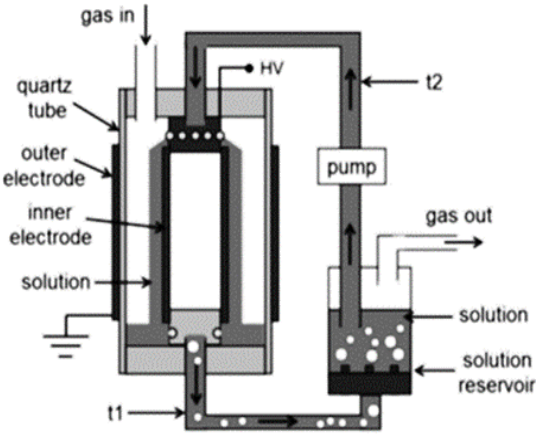

FIGURE 33. A pulsed power system for pentoxifylline degradation [113].

In this pulsed power system, a rotating spark gap switch was used to discharge the utilized 190 pF capacitor subsequently and adjust the frequency of the pulses. The generated voltage pulses had the amplitude of 12 kV, the rise time of 9ns, duration of 30ns and repetition frequency of 120 Hz. The delivered energy per each pulse was 10 mJ. The generated plasma discharges resulted in 92% pentoxifylline removal rate after 60 min treatment.

Treatment of wastewaters contaminated with analgesic drugs including non-steroidal anti-inflammatory drugs (NSAIDs), particularly ibuprofen, became an emerging issue nowadays due to large consumption of this medicine as a popular painkiller. Several advanced oxidation processes such as photoelectron-photon, ozonation, and sonochemical process were introduced for degradation of ibuprofen in wastewaters; however, some drawbacks of these methods, such as high power consumptions, hinder their efficient application for ibuprofen decomposition [114]. In contrary, the non-thermal plasma technique showed a great potential to degrade ibuprofen in wastewaters efficiently. A cylindrical wetted-wall reactor was used in [114] to decompose ibuprofen in a 500ml water solution. The developed plasma system included a high voltage stainless steel reactor with an inner diameter of 3 mm, a 25 cm graphite ground electrode with the inner diameter of 5 cm, a rotating spark gap switch and a DC power supply with adjustable voltage level (0-50 kV). The amplitude of generated pulses was 32 kV and the frequency was adjusted at 50 Hz, 75 Hz, and 100 Hz. The water solution was pumped into the system with 64 L/h flow rate. Fig. 34 shows the developed system. It was shown that the degradation process was faster when ibuprofen compounds with low initial concentration were used and a larger degradation rate was achieved using pulses with high repetition frequency. For ibuprofen with an initial concentration of 60 mg/l, the removal rate was 83% after 60min of treatment using 32 kV pulses with a frequency of 100 Hz.

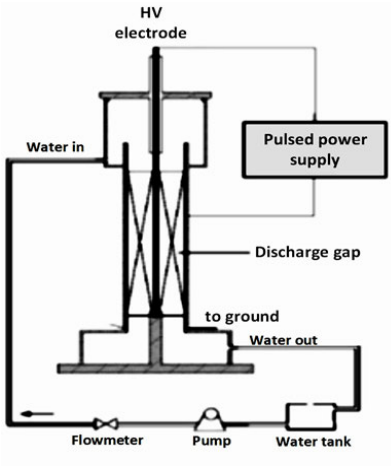

FIGURE 34. The plasma treatment system for ibuprofen decomposition [114].

A water surface discharge system was developed in [115] for ibuprofen degradation in 1000ml water solution. Compared to other water surface discharge systems, in this system, the water solution was sprayed on the high voltage electrodes. The developed system benefited from a uniform discharge, higher absorption of active species and less erosion of the high voltage electrodes that are due to the change in the injection of water solution to the system. As shown in Fig. 35, this system had three discharge reactors, Ra, Rb and Rc with one, two and multiple water spout, respectively.

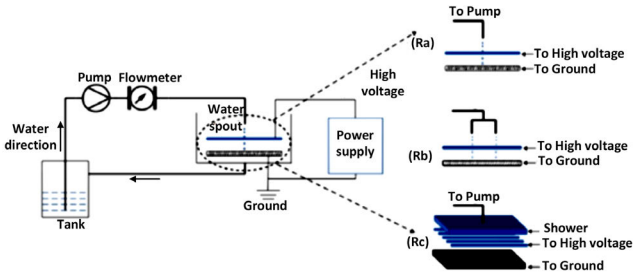

FIGURE 35. The block diagram of water drop induced discharge treatment system for ibuprofen degradation [115].

The discharge reactors with one and two spout comprised of a high voltage stainless steel electrode and a graphite plate as a ground electrode that separated by 1 cm. For the discharge reactor with multiple waterspouts, 15 stainless steel pipes formed the high voltage electrode and a stainless steel plate was used as a ground electrode. The distance between these two electrodes was adjusted between 0.5 cm and 3 cm. The high voltage electrodes were energized by pulses with an amplitude between 17-31 kV, repetition frequency of 100 pps, duration of 500 ns and the rising time of 60 ns. The experimental results showed that for a fixed water flow rate, increasing the voltage resulted in larger ibuprofen removal rate. Also, for the same input voltage, increasing water flow rate led to stronger discharge and more active species generation and consequently larger removal rate. The maximum reported ibuprofen degradation rate was 100%, achieved after 80min of treatment, using 31kV pulsed and with a flow rate of 0.95 L/min.

VIII. OTHER POLLUTANTS

Calcium carbonate is a chemical compound with low solubility in water that sediments when the water is heated up or concentrated. A large energy is required to disrupt the intramolecular bonding in calcium carbonate that results in calcium ions sediments and bicarbonate ions dissociation. In [116], a pulsed power system was used as a physical water treatment method to avoid calcium ions sediments in form of the adherent deposit that causes blockage in water flow and lower thermal efficiency in heat transfer equipment. The utilized pulsed power system generated high-frequency electrical pulses and a variable DC electric field. The experimental results showed that the pulsed power system could be successfully used to prevent calcium carbonate scale formation on the heat transfer surface of the developed prototype shown in Fig. 36.

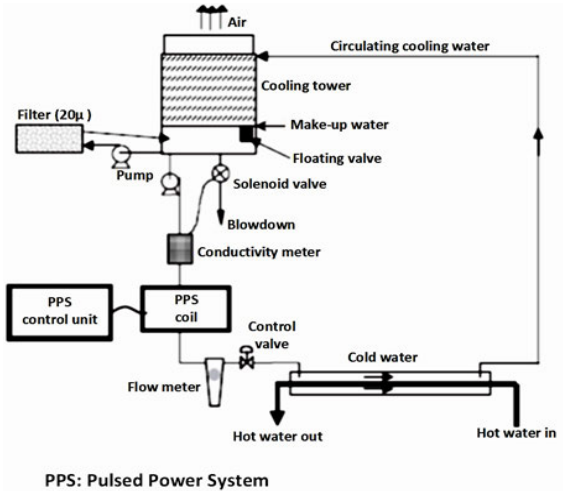

FIGURE 36. A pulsed power system for calcium carbonate treatment in water [116].

A three-stage Blumlein generator was developed in [117] to generate pulsed corona discharges. Each stage of this generator consists of two coaxial cables and a concentric electrodes reactor as shown in Fig. 37 and it was used to generate repetitive pulses (1-13 pulse per second) with 40-120 ns duration to remove NO form N2+O2+H2O mixture. The initial concentration of NO was 200 ppm. The relationship between NO removal energy efficiency, removal ratio and the pulse width were studied. It was shown that with lower NO removal ratio and narrower pulses, the removal energy efficiency was increased. The experimental results showed that with larger pulse repetition rate and pulse width, lower NO concentration is achieved. For instance, NO concentration dropped to 4ppm when the pulse repetition rate was 10 pps and the pulse duration was 120ns. In addition, it was shown that 27 g/kWh removal energy was required for 90% removal of NO when repetitive pulses (10 pps) with 40 ns duration were used.

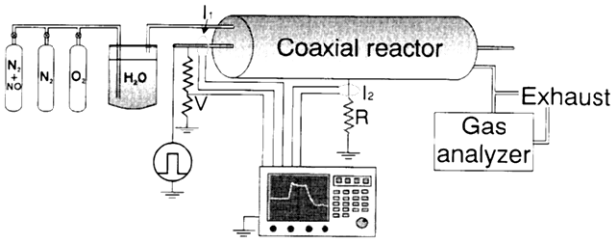

FIGURE 37. NO removal prototype with concentric electrode reactor [117].

In [118], a wastewater treatment system shown in Fig. 38 was developed using two dielectric barrier discharge (DBD) tubes for ozone generation. The utilized pulsed power supply generated 35 kV pulses with 50 Hz frequency. A mixture of wastewater, latex and washing detergent was used as a water sample for the treatment process. After 100 min treatment of 50 ml wastewater, the chemical oxygen demand (COD) was dropped by 13% while biological oxygen

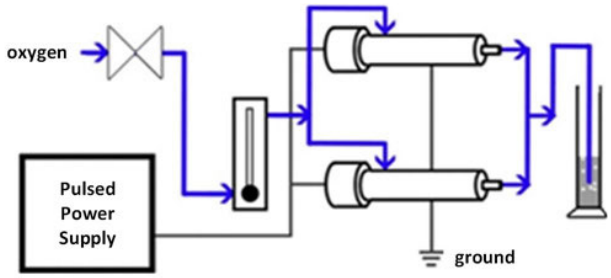

FIGURE 38. Ozonation system developed for wastewater treatment [118].

demand (BOD5) was increased after long ozonation. The initial concentrations of COD and BOD5 were 441 mg/l and 128 mg/l, respectively. The experimental results revealed that after ozonation treatment, the biodegradability of the wastewater was improved that is represented by higher BOD5 to COD ratio.

In [16] three needle-cylinder electrodes were developed to treat N-dimethyl-p-nitrosoaniline (RNO) with an initial concentration of 1.33×10^{-5} mol/L in 50ml wastewater using DC and pulsed corona discharges as shown in Fig. 39.

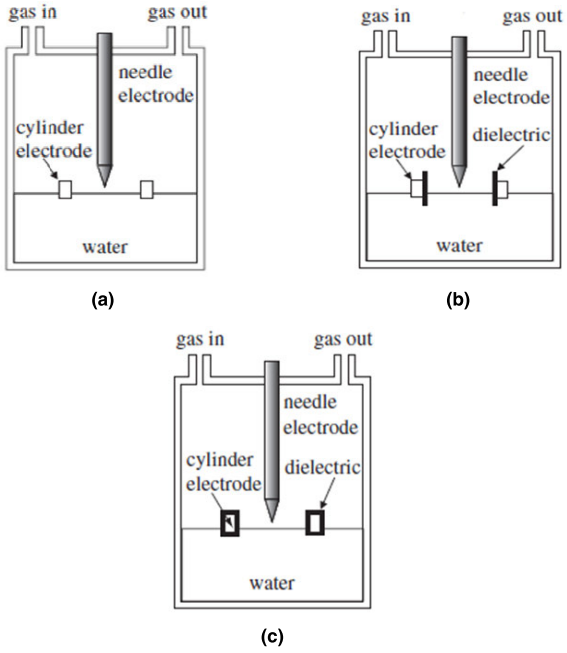

FIGURE 39. Pulsed corona discharge system for RNO treatment (a) DC corona discharge reactor, (b) and (c) pulsed corona discharge reactors [16].

For the DC corona discharge treatment method, the stainless steel needle electrode shown in Fig. 39(a) was energized by a high voltage DC signal. A brass grounded cylinder electrode is used for DC corona discharge. For the pulsed corona discharge generation, 9 kV pulses with a frequency of 1 kHz, the pulse duration of 200 ns and a rising time of 25 ns were applied. The results of DC corona discharge tests revealed that RNO reduction was 1.5×10^{-6} mol/L after

TABLE 1. Comparison of pulsed power systems developed for water treatment application.

TABLE I. COMPARISON OF PULSED POWER SYSTEMS DEVELOPED FOR WATER TREATMENT APPLICATION

Pollutants	Initial Concentration	Solution Volume	Treatment Method	Voltage Amplitude	Frequency	Pulse Duration	# Pulses	Electric Field	Decontamination Rate	Treatment Time	Ref
E. coli			pulsed UV	1 kV					0.43 log per mJ/cm^2		[56]
E. coli			EF			60ns,300ns, 2 us		164,107, 66 kV/cm			[57]
E. coli		250 ml	bipolar DBD and air bubbling	40 kV	50 Hz				99.98%	25 min	[61]
E. coli	10^7 cells/ml	50 ml	streamer discharge	23 kV	25 Hz	17 ms			7 log reduction	10 min	[62]
E. coli	10^7 cells/ml	50 ml	corona discharge	24 kV	25 Hz				7 log reduction	6 min	[63]
E. coli	10^3-10^7 cells/ml	300 ml	pulsed arc discharge and air bubbling	20 kV	100 Hz	150 ns			100%	5 min	[66]
E. coli	10^8 CFU/ml	10 ml	spark discharge plasma and EF	10 kV	30 Hz				8 log reduction	15 min	[67]
E-faecalis	10^8 CFU/ml	10 ml	spark discharge plasma and EF	10 kV	30 Hz				8 log reduction	12 min	[67]
E. coli		10 ml	corona discharge	120 kV	0.1 Hz	600 ns			3 log reduction 4 log reduction	after 8 and 15 corona discharge	[64]
B-subtilis		10 ml	corona discharge	120 kV	0.1 Hz	600 ns			4 log reduction	30 corona discharge	[64]
E. coli	10^4, 10^5, and 10^6 colonies		arc discharge	20 V	250 Hz				4 log reduction	2 min	[65]
E. coli	10^5 CFU/ml	1600 ml	UV radiation, corona discharge	23 kV	50 Hz				4 log reduction	15 min	[15]
E. coli	10^5-10^6 CFU/ml	2.8-4.75 ml	electric field	19 kV	70 Hz	200-ns FWHM	70	110 kV/cm	4 log reduction		[58]
B-subtilis	10^5-10^6 CFU/ml	2.8-4.75 ml	electric field	19 kV	70 Hz	200-ns FWHM	70	110 kV/cm	1 log reduction		[58]
E. coli	10^6 CFU/ml	250 ml	bipolar pulsed discharge	50 kV	50 Hz				98.5% inactivation efficiency	5 min	[59]
E. coli	10^{12} bacteria/l	1l	PEF	20 kV	1 Hz	60 ns	500		1 log reduction	after 500 pulses	[60]
Legionella Pneumophila microbes			pulsed corona discharge	80 kV	20 Hz	140 ns			5.4 log reduction	12.5 min	[68]
			PEF	(-)80 kV	20 Hz	240 ns			2.54 CFU/ml viable cells	25 min	[68]
Pseudomonas fluorescens	10^6 - 10^7 bacteria/l	0.5l	EF and corona	100 kV	1000 Hz	150 ns		70 kV/cm, 84 kJ	one log reduction		[70]
Bacillus cereus	10^6 - 10^7 bacteria/l	0.5l	EF and corona	100 kV	1000 Hz	150 ns		70 kV/cm, 500 kJ	one log reduction		[70]
Pseudomonas putida	10^8 CFU/ml	400 ul	EF	20 kV	0.3 Hz	600 ns	10 120-200		3.6 log reduction 6 log reduction		[71]
Microbial Pathogens	10^8 CFU/ml		streamer discharge	23.5 kV	124 Hz				<8 log reduction	30 s	[72]
Cyanobacteria Cells			pulsed streamer discharged	160 kV		2 us					[73]
Algae 10-50 µm microorganisms		1.59l	glow discharge	1.2 kV	10 kHz	5 us			10-50 µm algae microorganisms- 2 cells/ml, on day 0 and 5 cells/ml on days 5, Heterotrophic, E. coli bacteria decreased by 402 cells/ml and 0.07 cells/ml.		[74]
heterotrophic bacteria	591 cells/ml	1.59l	glow discharge	1.2 kV	10 kHz	5 us			reduced to 189 cells/100ml on day 0 and to 43 cells/100ml on day 5		[74]
E. coli	0.42 cells/ml	1.59l	glow discharge	1.2 kV	10 kHz	5 us			0.35 cells/100ml on day 0 and on day 5 no detectable cells		[74]
intestinal enterococci	0.60 cells/ml	1.59l	glow discharge	1.2 kV	10 kHz	5us			0.61 cells/100ml on day 0 and on day 5 no detectable cells		[74]
Nonylphenol ethoxylate	400ppm	500 ml	streamer discharge	39 kV		1.5 ns			100%	20 min	[78]

TABLE 1. *(Continued.)* **Comparison of pulsed power systems developed for water treatment application.**

phenol	1mM	15 ml	arc discharge	20 kV	250 Hz		17% TOC removal	30 min	[77]
sodium formate	1mM	15 ml	arc discharge	20 kV	250 Hz		100% TOC removal	30 min	[77]
phenol	1mM		pulsed corona discharges	40 kV	250 Hz	50 ns	91% by adding hydrogen peroxide, 69% by adding iron (III) sulphate , 40% by adding butanol		[79]
phenol			streamer corona discharge spark discharge	17.5 kV 20 kV	30 Hz 2.54 Hz	5 us	100%	75 min 100 min	[80]
phenol	50 ppm		Pulsed-streamer corona discharge	20 kV	48 Hz		100%	12.7 min 10.6 min with argon gas	[81]
phenol	1 mM/l		pulsed corona and catalyst	60 kV	500 Hz	100ns	33% one pass using Corona above water with 4-module 99% using aerosol reactor, 3 passes		[82]
phenol	50 ppm	200 ml	pulsed discharge plasma. Using Oxygen and argon as additive gases	30 kV	50 Hz		100% with oxygen flow	120 min	[83]
phenol	50 ppm	200 ml	pulsed streamer discharge	25 kV	100 Hz 600 Hz		60%-water surface plasma, 25%- streamer discharges, 15%- corona discharges	60 min	[37]
phenol	100 ppm	0.5l 1l	pulsed corona discharge	45 kV	60 Hz		97%, vitreous carbon ground electrode 97.5% ,stainless steel electrode and addition of potassium chloride salt	30 min 60 min	[84]
phenol	25 mg/l		pulsed corona discharge	40 kV	60 Hz		21 mg/l Pulsed corona discharge (PCD) 9 mg/l, using PCD+ ozone 8 mg/l using PCD+ silica gel 3.5 mg/l using PCD+ silica gel+ozone		[109]
2, 4 dichlorophenoxyacetic acid (2, 4-D)	10 mg/l		corona discharge	15 kV 25 kV	25 Hz		92% 100%	10 min 6 min	[85]
phenol	50 g/m^3	100 ml	gaseous corona discharge	16.7 kV DC			>99% when the ratio of CO_2 and O_2 was 3/7	1 hr	[86]
perfluoroalkyl acids	20 µM	1.4l	corona discharge	25 kV 16 kV	120 Hz 20 Hz		90% 25%	30 min	[87]
acetic acid	10 ppm		corona discharge	discharge voltage 8 kV	1 kHz	200ns	5.5ppm with oxygen discharge	20 min with oxygen bubbling	[88]
dye			pulsed DBD plasma	17 kV	130 Hz	130 ns	99% decolouration efficiency 83% unsaturated bond decomposition 74% chemical oxygen demand degradation rate	10 min	[90]
indigo carmine			pulsed corona discharge	25 kV	100 pps	70ns	chromogenic bond decomposition 100% indigo carmine decomposition	1 min 60 min	[91]
indigo carmine	250 mg/l		DBD	25 kV	200 Hz		100%	10 min	[92]
indigo carmine	20 mg/l		Pulsed Corona Discharge	25 kV	500 pps		100%	40 s	[93]

TABLE 1. ***(Continued.)*** **Comparison of pulsed power systems developed for water treatment application.**

indigo carmine	20 mg/l	1l	streamer discharge in air	28.2 kV	100 pps		100%	2 min	[89]
indigo carmine	20mg/l	500 ml	streamer discharge in gas	33 kV pulse voltage 2.78 kV charging voltage	50 Hz 10 Hz		100%	12 min 20 min	[94]
indigo carmine	20mg/l	1l	streamer discharge	13.5 kV charging voltage	1000Hz	100ns	95%	60 min	[95]
azo dye	1mM	100 ml	corona discharge	1 kV DC			96% 30%	60 min with $FeSO_4$ 90 min without Fe	[96]
azo dye	10mg/l	400 ml	pulsed-corona discharge	30 kV	50 Hz 75 Hz 25 Hz		about 58% 94.8% about 18%	60 min	[97]
Sunset yellow	50 mg/l	1l	corona discharge using copper mesh plate	30 kV	66.7 Hz	20us	100%	120 min	[100]
Amaranth	24 mg/l		discharge plasma	50 kV	50 Hz		81.24%	30 min	[101]
Rhodamine B (basic dye), Methyl Orange (acid dye), and Chicago Sky Blue	0.01g/l	300 ml	discharge plasma, spark, streamer, spark-streamer	20 kV	25 Hz		95%	100 min	[104]
organic dye Fluorescein-4-isothiocynate			arc discharge in water	900V	5 kHz				[105]
Acid Orange 7	20 mg/l		glow discharge	20kV	50 Hz		76.7% without activated carbon 96.1% with activated carbon	120 min	[102]
Acid Orange 142	20 ppm	100 ml	streamer discharge	12.5 kV DC			95.05%, pH=3 with Fe+2	20 min	[103]
Methyl orange	10 mg/l	50 ml	glow discharge plasma	6 kV	20 kHz		93%	15 min	[106]
azobenzene	10 mg/l	50 ml	glow discharge plasma	6 kV	20 kHz		85%	15 min	[106]
methylene blue	50 mg/l		streamer discharge	23 kV	25 Hz		100%	10 min	[107]
methylene	13.25 mg/l	20 ml	corona discharge	40 kV capacitor charging voltage	60 Hz		100%	120 min 25 min, adding O2 8 min, adding O2 bubbling containe d 1500 µmol O3/l	[108]
methylene blue	13.25 mg/l		pulsed corona discharge	40 kV	60 Hz		3 mg/l- pulse corona discharge(PCD) 1.1 mg/l - PCD+ α-alumina 0.47 mg/l-, PCD+ γ-alumina No detectable compounds- PCD+ silica gel		[109]
ampicillin, ibuprofen, fluoxetine and propranolol	100 mg/l for ampicillin, ibuprofen, propranolol 25 mg/l for fluoxetine		streamer discharge	71 V	1.65 MHz		90.91% Ibuprofen 100% Ampicillin Fluoxetine 99.66% Propranolol 99.64%	3 hrs	[112]
pharmaceutically active compounds, DCF, CBZ and CPF	1 mg/l	20 ul	pulsed corona discharge	25 kV	30 Hz		100%	4,6 and 8 min	[111]
pentoxifylline	100 mg/l	200 ml	coaxial dielectric barrier discharge	12 kV	120 Hz	30 ns	92%	60 min	[113]
Ibuprofen	60 mg/l	500 ml	corona discharge	32 kV	100 Hz		83%	60 min	[114]
Ibuprofen	10 mg/l	1000 ml	water surface discharge systems	31 kV	100 pps	500 ns	100%	80 min	[115]

TABLE 1. ***(Continued.)*** **Comparison of pulsed power systems developed for water treatment application.**

Persistent organic pollutants		1l	nanosecond pulsed discharge plasma	40 kV	600 Hz		35% TOC removal	3 hrs	[110]
Calcium carbonate			DC electric field						[116]
NO	200 ppm		pulsed corona discharge	42.2 kV	10 Hz	120 ns	4ppm		[117]
latex and washing detergent		50 ml	DBD	35 kV	50 Hz		concentration of COD dropped to 382 mg/l while BOD5 concentration increased to 182 mg/l	100 min	[118]
N-dimethyl-p-nitrosoaniline	1.33×10^{-5} mol/l	50 ml	DC corona discharge	9 kV	1 kHz	200 ns	$9*10^{-6}$ mol/L reduction rate	50 min, 0.3 W 25 min, 0.6 W	[16]

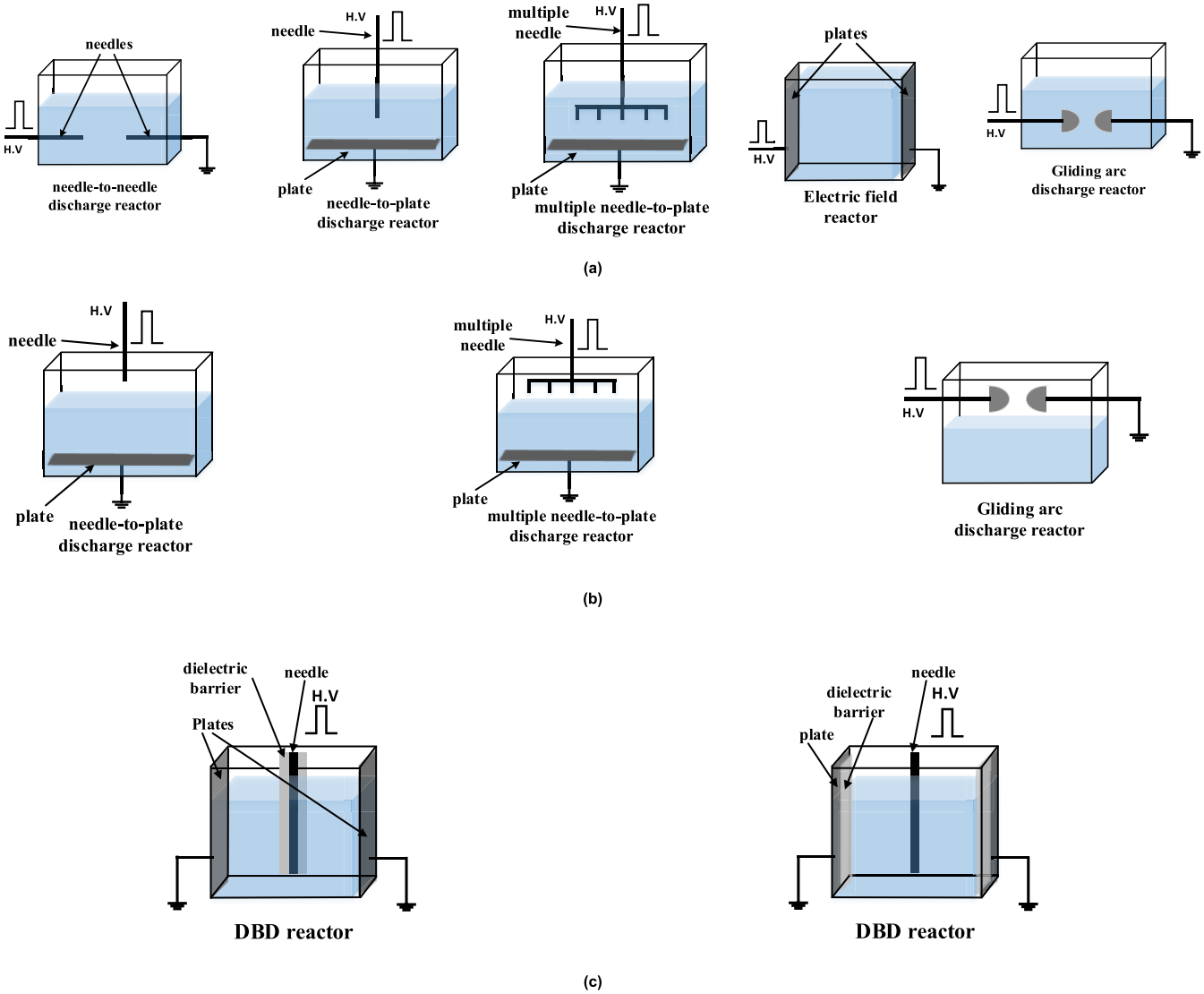

FIGURE 40. **Typical discharge reactors for water treatment (a) electrohydraulic discharge reactor (direct discahrge), (b) gas phase discharge reactor and (c) electrohydraulic indirect discharge reactor.**

38 min treatment using negative corona discharge with discharge power of 0.4 W. However, the reduction rate was 9×10^{-6} mol/L after 50 min and 25 min of treatment time using positive DC corona discharges with a discharge power of 0.3 W and 0.6 W, respectively. The results showed that at lower pressure, RNO reduction efficiency can be improved

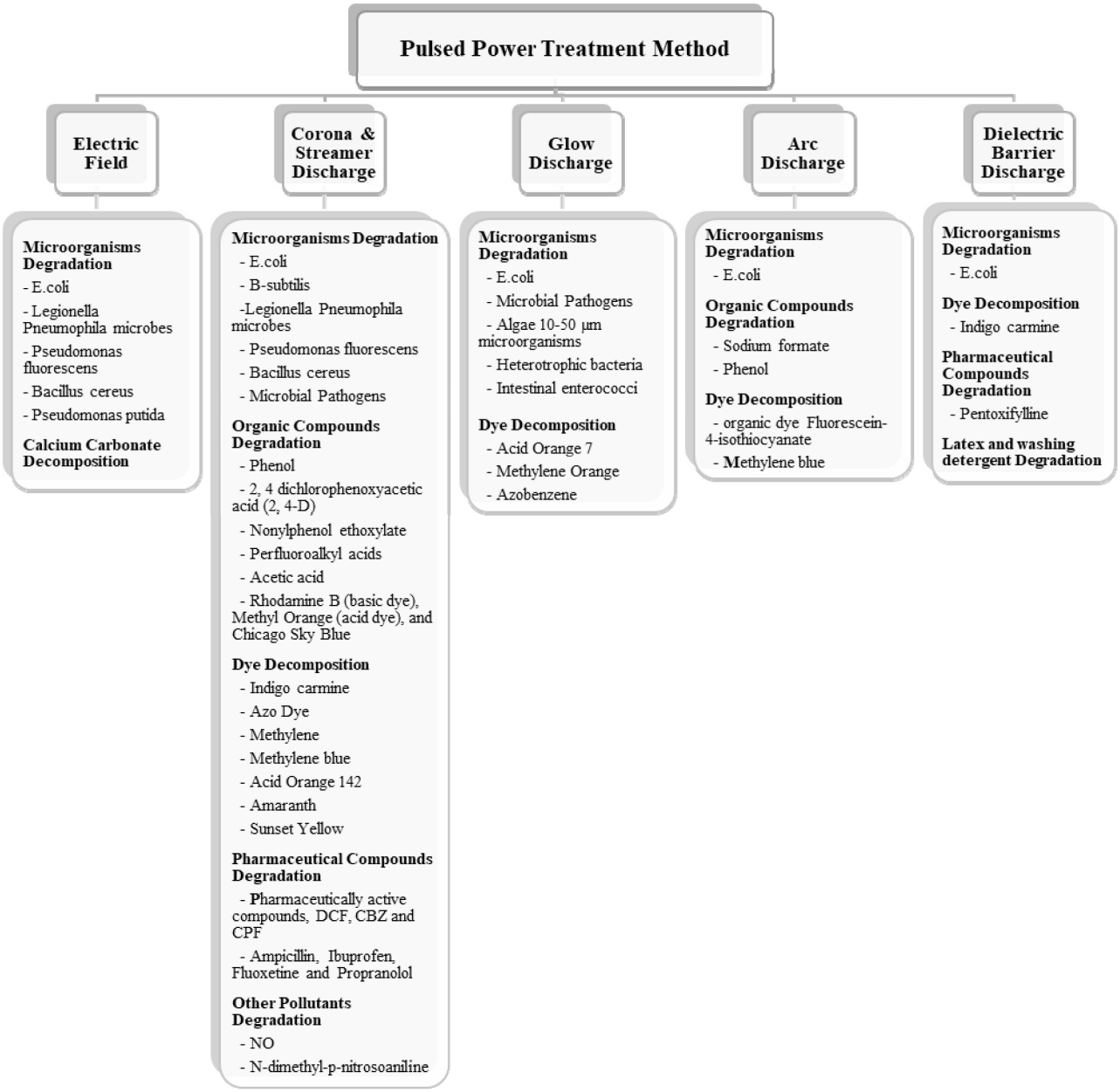

FIGURE 41. Summary of the proposed pulsed power treatment methods.

using pulsed corona discharge. The pulsed power system was also showed potential in the degradation of other bacteria including Legionella pneumophila, Pseudomonas, Bacillus, cyanobacteria, and E-faecalis.

IX. SUMMARY

This paper focused on water treatment applications using pulsed power systems. Table 1 compares pulsed power systems developed for water treatment application. Fig. 40 represents some of the typical discharge reactors introduced for water treatment. Fig. 41 shows the proposed treatment methods for wastewater applications using pulsed power system. Several pulsed power treatment systems have been developed for the decontamination of microorganisms, E. coli in particular. Developed pulsed power systems have been mainly used to generate high energy UV radiations, streamer discharges, corona discharges, arc discharges and pulsed electric fields to inactivate microorganisms in different applications. Applying high voltage pulses with high repetition frequency and energy density, narrow pulse width and the fast rise time will result in higher E. coli removal rate. Among the developed methods, the arc discharge system was found as an effective treatment system for degradation of E. coli bacteria over a short treatment period. Compared to arc discharges, corona discharges and pulsed electric field were also effective for E. coli degradation but over longer treatment times in order to deliver sufficient energy for bacteria cell membrane electroporation. The pulsed power system also

showed great potential in the degradation of other bacteria including Legionella pneumophila, Pseudomonas, Bacillus, cyanobacteria, and E-faecalis.

For the purpose of organic chemical compounds decomposition in water solutions, ozone and active hydroxyl and oxygen radicals are usually generated through gaseous and aqueous discharges because they can facilitate the organic compounds degradation process. To generate more free radicals, stronger UV radiations, corona, streamer, and spark discharges are required. To achieve this, high voltage pulses with narrow pulse width and high repetition frequency should be generated using proper pulse power systems. Different enveloping gasses such as oxygen, argon, and air can be utilized to facilitate the phenol decomposition process. Among these gasses, argon has the highest impact on phenol decomposition rate while higher oxygen flow rate decreases the phenol decomposition rate. Among the reviewed phenol degradation methods in water solutions, the highest degradation rate (97%) was achieved using pulsed corona discharged reactor. This reactor consisted of a planar ground electrode placed above the water surface and a high voltage needle-point electrode submerged in water solution. With more generated free radicals and ozone, the higher phenol degradation rate was achieved.

To increase the acetic acid decomposition rate, more OH radicals are required. To generate more OH radicals, the discharge input power, and the repetition frequency should be increased and high conductive solution should be used.

To treat the dye wastewaters produced by many industrial settings, several pulse power systems proposed consisting of different types of reactors and pulsed power generators. Pulsed corona discharge reactor, DBD reactor, corona reactor, coaxial reactor, multiple-electrode, and needle-to-plate reactors are used in different applications. Pulse corona discharge reactor is one of the widely used reactors in dye wastewater treatment systems. Several factors can improve the dye decomposition process such as high voltage pulses with high repetition frequency, high solution conductivity, and low pH. In addition to these factors, adding gas bubbles to the utilized reactor and using more reactors will facilitate the degradation process. In comparison between streamer, spark and spark-streamer discharge modes, it was shown that spark-streamer mode has a higher impact on the decoloration process.

Pharmaceutical compounds are widespread in hospital and residential wastewaters. Similar to other pollutants, the penetration of these compounds into the water environment should be avoided. In this regard, several plasma-based treatment systems were developed that could significantly degrade these pollutants in wastewaters. Among these compounds, Ibuprofen is more studied and mainly targeted for degradation in different literature. The results of these studies showed that for compounds with lower initial concentration, the degradation process is faster and higher repetition frequency contributes to a larger degradation rate.

The pulsed power technology presents a powerful potential for water treatment. The efficiency of the treatment process can be highly affected by several factors including pulse parameters (amplitude, frequency, bandwidth and number of pulses), reactor configuration, solution properties (conductivity, pH level) and treatment duration. All of these factors should be properly studied and designed for different applications in order to achieve efficient treatment process.

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