Innovative Methods for Energy-Efficient Excitation of Pulsed Electric Discharge in Water Medium and Their Possible Applications

Elchin Gurbanov
Baku Engineering University,
Baku, Azerbaijan
elqurbanov@beu.edu.az

Farida Gasimova
Baku Engineering University,
Baku, Azerbaijan
fqasimova2@std.beu.edu.az

Khanim Rustamova
Baku Engineering University,
Baku, Azerbaijan
xrustemova1@std.beu.edu.az

Abstract— **The article is devoted to the methods of energy-efficient excitation mode of pulsed electric discharge in the water medium and their application for environmentally friendly disinfection of pathogenic microorganisms contained in it. An innovative electrode system "pin-plane" with a sharply non-uniform electric field using various moving dielectric cap on the potential pin-electrode is proposed. It is shown that the movement of the cap relative to the lower surface of the "pin" electrode contributes to the focusing of the electric field in the water gap and uneven distribution of the intensity of discharge processes along the surface of the dielectric cap. This, in turn, leads to an expansion of the zone of ionization processes, generation of optical radiation, chemically active discharge products and the formation of high-speed mechanical waves, which in combination negatively affect the survival of pathogenic microorganisms contained in the water medium.**

Keywords—pulsed voltage, electrode system, pin-plane, inactivation of pathogenic microorganisms, mechanical wave, optical radiation, chemically active discharge products

I. Introduction

At present, great attention is paid to the development of energy-efficient installations and technologies that allow for a fairly short period of time to obtain a large specific energy input into various technological processes. In this aspect, one of the methods for obtaining high energies is the generation of super-powerful high-voltage pulses of micro- and nanosecond duration for their various applications [1]. For example, in some articles, the authors use the generation of high-voltage pulses to crush super-hard rocks, to clean surfaces subjected to corrosion, to obtain biomass in a finely dispersed form for their further use in agriculture as a fertilizer [2-4]. Some works are devoted to the sterilization of medical instruments using strong pulsed electric fields and discharges [5]. In works [6-8], the authors pay attention to the effect of nanosecond pulsed fields on fluid food products in order to disinfect them from pathogenic microorganisms and extend their shelf life while preserving their biological value. All the above methods and technologies are aimed at energy-efficient impact on the object of study and environmentally friendly impact, which is very important today in connection with climate change and the violation of the ecological balance on our planet.

II. The background of implementation.

In scientific research, high-voltage pulses of microsecond duration in water medium and pathogenic microorganisms of 1 μm in size were chosen as objects of study. The aim of the research was a comprehensive approach to identifying the causes of the impact of strong electric fields and discharges on the process of inactivation of pathogenic microorganisms in the aquatic environment. To achieve this goal, a high-voltage installation with a pulse voltage generator based on pulse capacitors with a capacity of 0.1 μF, a charging voltage of 10 kV each and an output voltage of 40 kV was developed and assembled (fig.1).

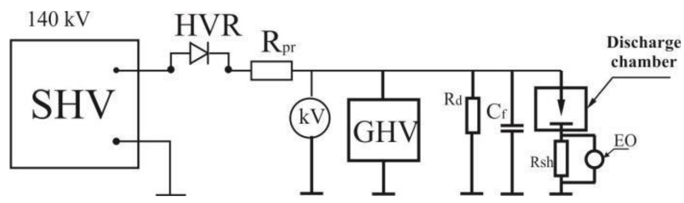

Fig.1. Electrical scheme of high-voltage pulse installation: SHV-high voltage source; HVR – high voltage rectifier; GHV - high voltage pulse generator; EO- electronic oscilloscope

A ―pin-plane‖ module with a fluoroplastic cap moving relative to the end of the potential ―pin‖ electrode was used as an electrode system. A high-voltage pulse of microsecond duration and 40 kV amplitude was fed into the discharge chamber onto the potential electrode, after which a spark discharge was initiated in the water medium. The asymmetric

―pin-plane‖ electrode system creates a sharply non-uniform electric field, under the influence of which free particles present in the water are accelerated along the free path, accumulate energy to perform the ionization act. In experiments on the potential pin-electrode, a fluoroplastic dielectric cap is used, facilitating the excitation of discharge processes in the interval with a short delay time, expansion of the ionization zone and initiation of ionization processes far from the initial ionization centers (fig.2).

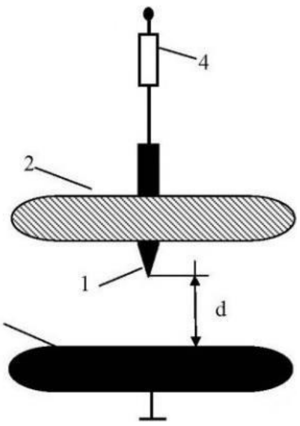

Fig.2. Electrode system rod plane with a dielectric attachment on the potential electrode: 1 - pin electrode; 2 - moving fluoroplastic attachment; 3 - metal plate; 4 - current-limiting resistor

The mechanism of stable discharge ignition occurs due to the accumulation of negative ions on the surface of the cap (due to electrostatic forces) and their disintegration in the overstressed water gap with the emission of free electrons into the discharge gap [9]. This allows stable ignition of the discharge and expansion of the ionization zone both along and across the water gap. The use of a dielectric cap also allows focusing the electric field in the gap and coordinating the size of the ionization zone, which is very important when designing a reactor for disinfecting the water medium from pathogenic microorganisms.

It should be noted that by changing the amplitude of the pulse voltage and, accordingly, the electric field strength, it is possible to initiate discharge processes both from the cathode and from the anode. In the experiments, a photographic study of individual stages of discharge in water was also carried out to identify the physical mechanism of breakdown of the water medium.

As noted earlier, Chlorella Vulgaris cells, which are constantly found in water, were used as the object of study. The initial cell concentration in the water medium (before exposure to high voltage pulses) was $2*10^9$ cells/ml. When exposed to microsecond high voltage pulses, the cell concentration sharply decreased and did not recover for a certain period of time, as shown in fig. 3.

It should be noted that the effect of high voltage pulses of microsecond duration did not cause heating of the water medium more than 40^0S. Each sample of the culture medium (the original and the one subjected to pulsed action) was divided into 3 parts. Then, each of them was placed separately in the chamber for the growth of microorganisms. It was found that when exposed to pulsed fields with a strength of 35 kV/cm, it contributes to a significant slowdown in the process of increasing the concentration of microorganisms (fig. 3, b). It is very important to emphasize that the increase in temperature does not affect the process of increasing the concentration in any way. Only the specific action of strong pulsed electric fields has a significant effect on the process of cell growth. Thus, it can be concluded that the microsecond effect of pulsed fields on the cells of microorganisms leads to both inhibition of the cell growth process and stimulation of proliferation, which is affected by the applied field strength.

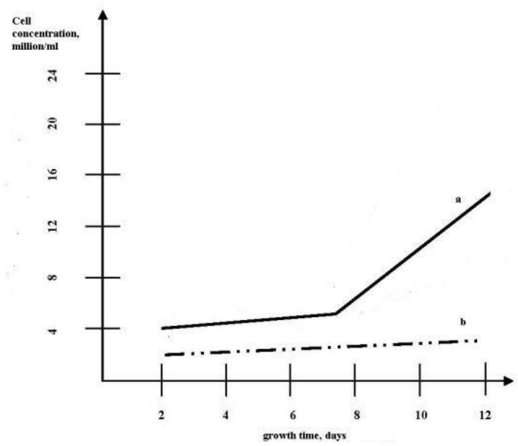

Fig.3. Experimental data on the degree of inactivation of pathogenic microorganisms in water medium: a) before pulse exposure; b) after pulse exposure

Now let us consider the physical mechanism of the effect of strong pulsed electric fields of microsecond duration on the process of inactivation of pathogenic microorganisms in the water medium. For this purpose, let us consider in more detail the process of initiation of discharge channels in water. As is known, even in a thoroughly purified liquid medium there are dissolved gases. Let us recall that the dielectric permittivity of gases is much less than of water one and is equal to unit. As a result, when pulsed electric fields act on the water gap, the maximum electric field will be concentrated in places with low dielectric permeability (gas inclusions), leading to the initiation of ionization processes in them. The process of impact ionization in gas inclusions leads to the emergence of fast electrons, which, in turn, accelerate the ionization process under the influence of a strong field and the expansion of the ionization zone. As mentioned earlier, the use of a dielectric cap made of fluoroplastic on potential pin-electrode corrects the timely emission of free electrons into the discharge channel due to the decay of negative ions accumulating on the surface of the dielectric. With the generation of electrons, the heated gas inclusions begin to expand due to the high pressure inside it. In this case, the so-called boiling of the water medium occurs, as shown in figure 4. This process leads to cooling of the discharge channel and, as a consequence, to the collapse of the gas inclusion, i.e. cavitation. As a result, high-speed mechanical waves are formed in the water medium, which have a detrimental effect on the vital activity of bacteria contained in the water.

On the other hand, in addition to impact ionization in gas inclusions, excitation of neutral gas atoms with subsequent generation of photons, as well as recombination processes with the formation of neutral atoms occur. As a result of all these physical processes, powerful optical radiation (infrared, light, ultraviolet) occurs, which in combination also negatively affects the vital activity of pathogenic microorganisms contained in water. It should also be noted that in the process of various types of ionization, chemically active discharge products (ozone, atomic oxygen, etc.) are formed, accelerating the process of inactivation of microorganisms in the water nedium.

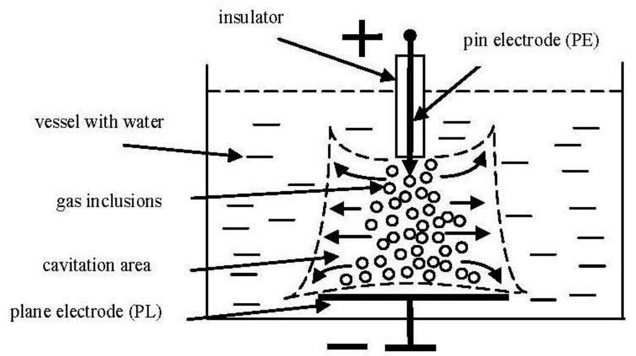

Fig.3. Description of the mechanism of the discharge process in water medium under the influence of high voltage pulses

Now let's consider some physical aspects of the impact and distribution of strong pulsed electric fields directly inside the cell itself. It should be noted that the cell itself also consists of components with different dielectric permeability. Considering that the cell lives in an water medium with a dielectric permeability of ε=80, it is necessary to know the comparative values of the dielectric permeabilities. of all the elements present (water and microorganisms) for the correct and optimally advantageous distribution of strong electric fields in the objects of study under consideration.

Thus, the cell of a microorganism consists of three components (fig.4): an outer membrane (2) with a dielectric permeability of ε_m and radius R_1, a cytoplasm (3) with a dielectric permeability of ε_c and radius R_2, and a nucleus (4) with a dielectric permeability of ε_n and and radius R_3. From this point of view, knowledge of the relationships between the dielectric permeabilities of individual cell components and the dielectric permeability of the inhabited environment (1) is very important for the correct calculation of the load of a high-voltage pulse installation and the determination of the optimal energy-efficient mode of its operation.ë

As is known from high-voltage technology, if a dielectric medium is exposed to strong electric fields, it is polarized. In our case, the polarized medium is a microorganism cell with its components with different dielectric permeabilities. The main protective side of the cell is its outer membrane (2), which is capable of withstanding strong electromagnetic influences and voltage drops on it.

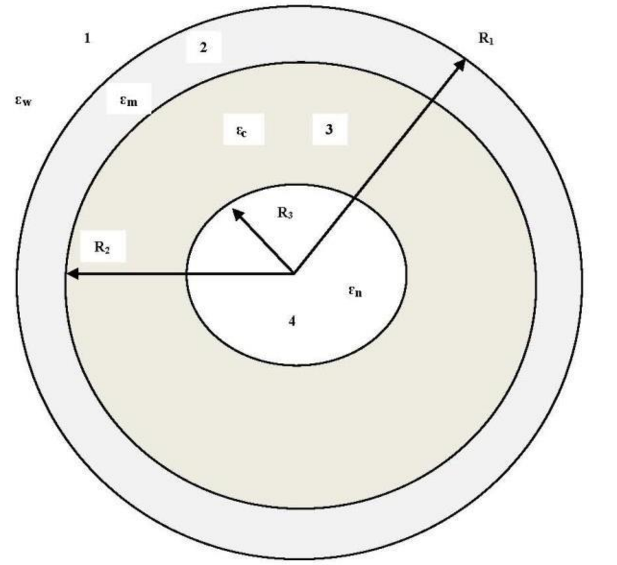

Fig.4. Spherical model of a microorganism cell

It should be noted that for a comprehensive effect on all components of the cell, it is necessary to correctly select the frequency range of the high voltage pulse. It has been established that the signs and densities of charges accumulated at the interphase boundaries between individual cell components, as well as the potentials created by them, depend in a complex way on the values of the permeabilities of individual cell components. Thus, if the smaller the value of the dielectric membrane - ε_m compared to the permeability of the inhabited water medium - ε_w and the cell cytoplasm – ε_c, the greater the field strength will be concentrated on the outer shell (2) of the cell. Otherwise, the field on the outer membrane will be weakened. As for the voltage drop on the outer membrane, it will increase with the growth of the permeability of the inhabited water medium – ε_w compared to the permittivity of the outer shell – ε_m.

Thus, summing up the results of the conducted experimental scientific research on the influence of strong pulsed fields on the water medium for the purpose of its disinfection from pathogenic microorganisms, we can conclude the following:

1) The impact of strong pulsed fields on the water medium causes a whole complex of physical, chemical and mechanical processes, including ionization processes in dissolved gas inclusions in the aquatic environment with the formation of highly conductive streamer channels with violent impact ionization and optical radiation, the formation of high-speed mechanical waves, etc.;

2) The development and implementation of an innovative ―pin-plane‖ electrode system with a moving dielectric cap allows focusing the pulsed electric field, optimizing the energy-efficient mode of action on the objects of study, ensuring the expansion of the ionization zone due to the decay

of negative ions accumulating on the surface of the dielectric cap and the violent injection of free electrons into the discharge zone;

3) Experimental results were obtained with the drawing of curves of the dependence of cell concentration on the time before and after high-voltage microsecond pulse exposure. It was revealed that after exposure to powerful electromagnetic fields and discharges, a sharp decrease in the concentration of pathogenic microorganisms is observed and this is maintained for a long period of time;

` 4) A set of physical mechanisms is proposed that facilitate the process of inactivation of pathogenic microorganisms: effect of high-frequency pulsed fields and discharges, the generation of high-frequency optical radiation in discharge channels, the formation of high-speed mechanical waves during the collapse of gas inclusions in water medium, the generation of chemically active discharge products, etc.

4) The structure of the cell, the electrophysical parameters of its components were studied and the relationship between the cell and the electrical parameters of the pulse was established. Such a consistency of the electrical parameters of the high-voltage installation and the electrophysical parameters of the cell allows optimizing the energy-efficient impact of strong pulse fields and discharges on the object of study.

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