JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(6), 28–35
https://doi.org/10.12911/22998993/201436
ISSN 2299–8993, License CC-BY 4.0

Received: 2024.02.13
Accepted: 2025.04.05
Published: 2025.04.15

Optimizing electric discharge cavitation processes as green solution for environmental safety

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ABSTRACT

The electric discharge in special cavitation mode is an effective instrument for water disinfection, intensification of extraction, and material dispersion. The object of this work was to study the influence of individual elements and characteristics of electric discharge installations on the intensity of electric discharge cavitation. The influence of electric discharge installation parameters and the constructive features of the working chamber on the intensity of electric discharge cavitation was considered. Simple ways to increase cavitation intensity during special modes of electric discharge were shown. The dependence of the intensity of electric discharge cavitation on design features of the technological part of the installation: working chamber and electrode system was shown. The use of an electrode system with a movable plain electrode-cathode allows increasing intensity of cavitation. Increasing the level of liquid above the electrode system leads to a decrease in the intensity of cavitation, and increasing of surface area of liquid in the working chamber allows increasing intensity of cavitation significantly. The obtained results open up practical prospects for the use of electric discharge cavitation under the conditions of industrial chemical-technological processes. The research demonstrates that optimizing electric discharge cavitation processes aligns with the principles of green solutions for environmental safety, providing effective and sustainable approaches for industrial applications such as water treatment, material processing, and chemical-technological processes.

Keywords: electric discharge, cavitation, water treatment, processing equipment, green solution.

INTRODUCTION

For at least the last two millennia, the quality of natural water has been gradually deteriorating and has reached a level of pollution at which human use is limited or the water may be hazardous. This deterioration was firstly associated with rapid urban development in certain areas of the Earth, but long-range atmospheric transport of pollutants has now changed this picture: even remote areas can be indirectly polluted (Pohrebennyk et al., 2017; Mitryasova et al., 2021; Bernatska et al., 2023). The treatment of microbiologically hazardous wastewater and natural waters for their disinfection is one of the most important and urgent actions for water pollution control (Mitryasova et al., 2020; Petrichenko et al., 2024; Water Security, 2021). Wastewater disinfection is the process of destroying pathogenic microorganisms that may pose a threat to human health and the environment. This stage of water treatment is necessary to prevent the spread of infectious diseases and protect ecosystems. There are various methods of wastewater disinfection, they can be divided into physical, chemical, and combined. The choice of method depends on the following factors: the volume and composition of water to be treated, the degree of contamination, requirements for water quality after treatment, the availability of equipment, and financial capabilities.

The most well-known and widespread physical water disinfection method in everyday life is thermal. Due to its high cost, this method is not used on an industrial scale. However, recently attempts have been made to reduce energy costs for its implementation by pulsed (pulsating) heating (Singh et al., 2017). A striking example of modern physical methods of water disinfection is ultraviolet (UV) irradiation. UV radiation destroys the DNA of microorganisms, preventing their reproduction (Paidalwar & Khedikar, 2016).

This method is popular due to the absence of chemical reagents, ease of use, and high efficiency against most pathogens. In addition, the advantages of the method are its environmental friendliness, and the absence of by-products, but its efficiency is highly dependent on the transparency of the water, and is also associated with the need for regular expensive maintenance of UV radiation sources. Chlorination is the most common chemical method of disinfection. In this method, chlorine compounds (for example, bleaching powder, and sodium hypochlorite) are added to water. An active oxidizer destroys microorganisms by destroying their cellular structures. The advantages of this method are availability, and prolonged disinfection (residual chlorine continues to act in the water supply network). On the other hand, the method is characterized by the active formation of toxic by-products (trihalomethanes), and is also harmful to the vital activity of some types of aquatic organisms (Mazhar et al., 2020).

A more advanced chemical method is ozonization. Ozone, as a powerful oxidizer, destroys the membranes of bacteria and viruses (Gray, 2014). Ozonization is effective against most pathogens and leaves no harmful by-products in water. However, the equipment for ozonization is expensive, whereas ozone production and transportation are highly hazardous processes.

Modern water purification systems often use combinations of methods to achieve the best results. In particular, effective solutions for cleaning the environment from pollutants of biological origin have been proposed using plasma in liquid (Zver et al., 2023; Foster, 2017; Moreau et al., 2008). The action of plasma on the water being disinfected uses both several physical phenomena (heating, ozone formation) and chemical action (formation of oxidizers).

High-voltage electric discharge in liquid is one of the relatively simple tools for creating a plasma state of matter and is accompanied by a wide range of physical and chemical phenomena. Using high-voltage electric discharge in liquid in water disinfection technologies, extraction of target substances from plant materials, fine grinding (Malyushevskaya et al., 2022, 2023; Sato, 2008; Anuntagool et al., 2023; Bereka et al., 2020) and integrating high-voltage electrical discharge treatment into existing production processes, the consumer is invariably faced with questions about the influence of technological factors on its performance and processing efficiency.

The technological features of electric discharge processing of materials vary depending on the goal pursued. In the case of using high-voltage breakdown in contaminated water for its disinfection, it has been experimentally proven (Malyushevskaya et al., 2023) that the driving force of the disinfection effect is high-intensity electric discharge cavitation. In addition to understanding the global mechanisms for increasing the intensity of electric discharge cavitation shown further in (Malyushevskaya et al., 2024) it is necessary to identify the features of the implementation of the cavitation mode of electric discharge under the conditions of real charging and discharging circuits of an electric discharge installation and different designs of technological equipment (working chambers, electrodes) to maximize the efficiency of electric discharge action.

The object of this work was to study the influence of individual elements and characteristics of electric discharge installations on the intensity of electric discharge cavitation.

MATERIALS AND METHODS

An electric discharge device was used during the experiment (Fig.1). The high-voltage pulse current generator was connected to an industrial three-phase network. The generator contained three identical inductors 1, three identical high-voltage capacitors 2, a three-phase high-voltage rectifier 3, a capacitive energy storage device 4, a high-voltage switch 5, a working chamber and a system of electrodes 6, and a protection system 7. The high-voltage pulse current generator was equipped with a three-phase frequency converter 8 and a separating capacitor 9.

The electrode system 6 was placed in the working chamber along its vertical axis. The anode was a metal rod placed in a fluoroplastic

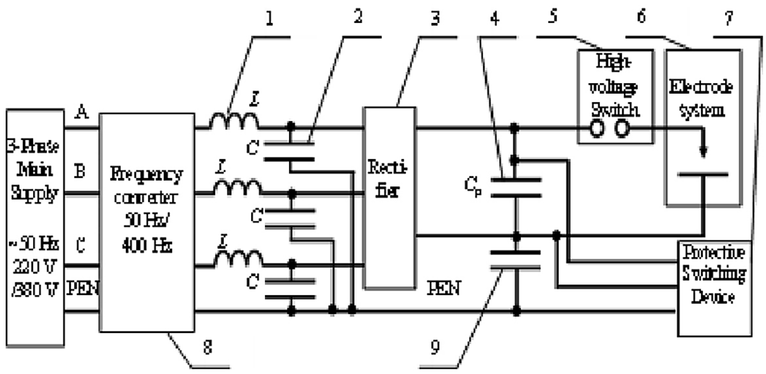

Figure 1. Laboratory electric discharge installation (Vinnychenko et al., 2024)

insulating casing, the anode diameter was 8 mm, and its tip was sharpened in the form of a hemisphere with a radius of 4 mm. The working chamber was a metal parallelepiped with windows made of durable organic glass for observing the processes occurring in the liquid during an electric discharge. The bottom of the metal working chamber was a counter electrode − a cathode.

The design of the working chamber provided the ability to evaluate the intensity of electric discharge cavitation by varying:

- the degree of mobility of the electrode-cathode;
- the level of the working medium (H) above the electrode system;
- the surface area of the liquid in the working chamber (S), which was changed by moving the chamber from a vertical to a horizontal position.

The experiments were carried out with the following fixed parameters: the length of the discharge gap l_p = 15 mm, the capacity of the energy storage device (capacitor bank) C = 0.4 μF; the specific resistance of the working liquid − 19.5 Ohm·m; the repetition rate of discharge pulses – 0.5 Hz. In the course of the processes of electric discharge cavitation optimization, the pulse repetition frequency of 0.5 Hz, as well as other electrical parameters of liquid processing, were chosen close to those previously determined in (Malyushevskaya et al., 2023) as effective electric discharge modes, which enable water disinfection with a manifold reduction in processing time and the content of chemical reagents. A distinctive feature of electric-discharge water disinfection in a special cavitation mode is its high speed. During the processing time, the volume of liquid in the working chamber does not have time to heat up to the temperatures critical for the survival of biological objects. Initial temperature of liquid in working chamber was 20 °C, liquid processing time 20–30 s, so by the end of processing the temperature of the liquid was 22–23 °C; specific energy of processing remained constant and equal to 25 kJ/dm^3. The charging schemes of the energy storage device (capacitor) and the charging voltage of the capacitor U_0 = 20–25 kV were varied. The base level of the liquid above the upper point of the discharge gap was 30 mm, and the base position of the chamber was vertical.

At the final stage of the electric discharge, a significant number of gas bubbles of various sizes are formed in the working fluid, this phenomenon is visually recorded quite accurately. The number of bubbles is proportional to the cavitation intensity, so this intensity was quickly visually estimated using the coefficient K (%). This coefficient was determined by the ratio of the area occupied by cavitation bubbles to the total area of the observation window. The coefficient K was determined using a stencil with a 100 × 100 mm^2 window, with horizontal and vertical scales applied, fixed to the side wall of the chamber symmetrically to the axis of the electrode system. Accurate determination of the cavitation intensity was then carried out using the method described in (Yushishina et al., 2002), which provides for iodometric determination of cavitation intensity by the release of J2 from a KJ solution. The concentration of KJ in the initial aqueous working solution was 1 g/dm^{-3}. The samples for measuring the released J2 were taken every 500 pulses, the amount of released J2 was determined by volumetric titration with sodium thiosulfate, using starch as an indicator. Each series of measurements included 10 repetitions, then the results were processed using statistical methods.

RESULTS AND DISCUSSIONS

The effect of the capacitor bank charging circuits, varying as shown in Figure 2, on the intensity of electric discharge cavitation was studied. Circuits 1, 1A, 2, and 2A provided the capacitors charging directly through the processed liquid, and circuits 3, 3A, 4, and 4A – the capacitors charging according to the usual (direct) circuit. The rest of the elements and parameters of the charging and discharging circuits remained unchanged. The obtained results are presented in Table 1, "non-breakdown" means that the discharge of the capacitor bank was not accompanied by the formation of an electric breakdown channel in water. It should be noted that during the experiment, when reconnecting according to Figure 2, small changes in the inductances of the connecting elements were not taken into account.

Pulse current generators are a battery of charged capacitors, the number, voltage, and capacity of which determine the energy stored in a pulse. Energy enters the capacitor bank from the charger and accumulates in it over a relatively long period, and is released over a relatively short period in the object of treatment. When designing a pulse current generator, one usually proceeds from the requirements of the experiment. In the considered case, the hypothesis was tested about the possibility of forming an additional number of bubbles - cavitation embryos due to the flow of charging current in the liquid in the working chamber. It was assumed that such preliminary heating and ionization of the liquid at the pre-breakdown stage would contribute to the development of more powerful cavitation at the post-breakdown stage of the discharge.

Connection schemes 1, 2A, 3A, and 4 do not allow obtaining an electrical breakdown of the working fluid. As it was shown (Malyushevskaya et al., 2023), the formation of an electrical breakdown channel and, then, a vapor-gas cavity in the liquid is a mandatory condition for generating cavitation of any intensity at the final stage of the discharge. That is, such connection schemes cannot be used in technologies using an electrical discharge in the cavitation mode. According to the obtained data (Table 1), the efficiency of schemes 1A, 2, 3, and 4A in terms of cavitation intensity is comparable; however, scheme 3 is the most acceptable for laboratory research and technological use, as the safest. A small advantage of using scheme 2 in terms of the intensity of generated cavitation cannot be the reason for its use outside the laboratory with special safety measures.

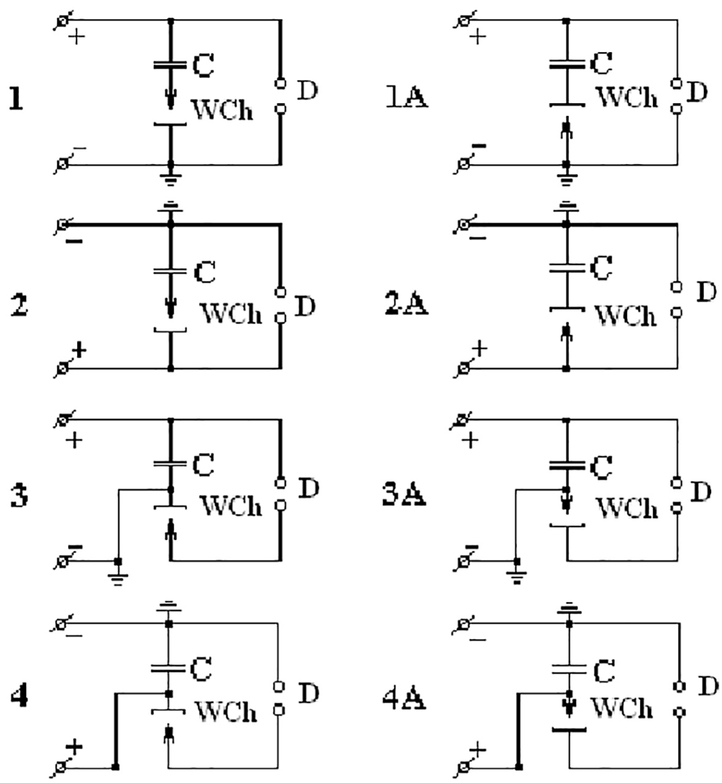

Figure 2. Energy storage device (capacitor bank) charging schemes: *C* – battery of capacitors, *D* – discharger, WCh – working chamber

Table 1. The influence of energy storage device (capacitor bank) charging schemes on the intensity of electric discharge cavitation

Cavitation intensity, % Charging voltage on the capacitor bank, kV			
Number of scheme	20	22.5	25
1	Non-breakdown	Non-breakdown	Non-breakdown
1A	17	27	37
2	19	29	39
2A	Non-breakdown	Non-breakdown	Non-breakdown
3	15	26	38
3A	Non-breakdown	Non-breakdown	Non-breakdown
4	Non-breakdown	Non-breakdown	Non-breakdown
4A	17	27	36

The design features of the electrode system also have a significant impact on the intensity of cavitation. Two design schemes of the electrode system were studied: tip-fixed plane (rigidly fixed electrodes), and tip-movable plane. To implement such an electrode system, a spring-loaded metal plate was fixed to the bottom of the working chamber, covering the entire area of the bottom.

The intensity of electric discharge cavitation with a "movable" element of the electrode system for all capacitor charging voltages is higher than for rigidly fixed electrodes. Probably, the intensity of cavitation increases due to the more active formation of turbulent hydro flows in the working environment and subsequent intensive mass transfer of chemically active particles that are formed due to cavitation. In (Kosenkov, 2014) a similar design of the working chamber with a movable element was used to determine the mechanical strength of the element. The author's goal was to develop the use of an electric discharge to deform metal plates. However, in the course of this work, the author notes that the refusal to rigidly fix the deformable plate, which in his case was also the cathode, leads to a sharp increase in post-discharge cavitation (Fig. 3).

The influence of the working liquid level above the electrode system on the intensity of electric discharge cavitation for different values of the capacitor charging voltage was revealed. The results are shown in Figure 4. With an increase in the liquid level above the discharge gap, the intensity of electric discharge cavitation decrease,s since the influence of local shock waves reflected from the liquid surface decreases and the degree of hydrodynamic impact on the processed liquid decreases.

Such observations are also discussed in the paper (Fernandes et al., 2024), which studies the influence of different ultrasonic projector geometries on cavitation generation at varying levels of electrical power. The authors note that moving the sensors horizontally and vertically in the chamber (changing the distance between the rigid

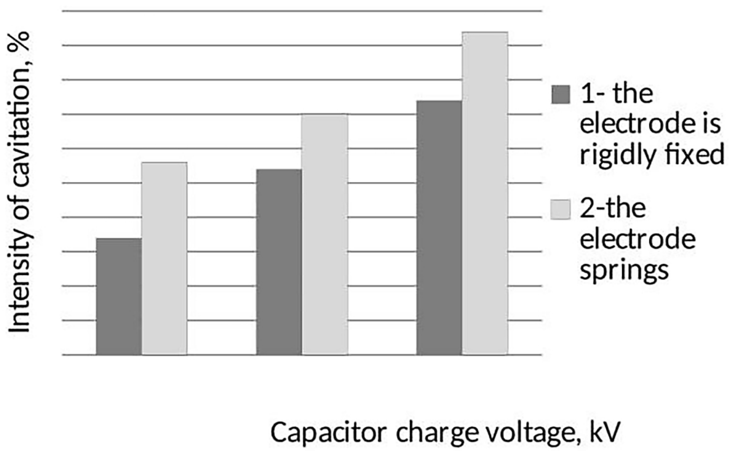

Figure 3. The influence of the electrode system design on the intensity of electric discharge cavitation

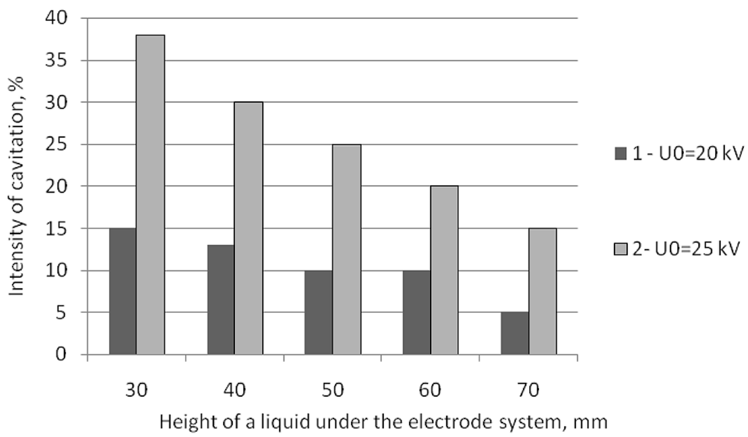

Figure 4. Dependence of the intensity of electric discharge cavitation on the level of the working fluid above the electrode system

walls of the chamber and the surface of the liquid) also affects the process of cavitation generation.

Another relatively simple way to change the intensity of electric discharge cavitation is to vary the area of the free surface of the liquid in the working chamber. The effect of the area of the free surface of the medium (S) on the intensity of electric discharge cavitation is quite significant. Figure 5 shows the dependence of the intensity of electric discharge cavitation on the surface area of the working medium for vertical and horizontal arrangement of the chamber for different capacitor charging voltages. With a fixed base height of the working liquid level above the electrode system, this is noticeable for all capacitor charging voltages from the range under study.

In the experiment under discussion, with a vertical chamber arrangement, the liquid surface area equaled Sv = 3.6 dm^2, with a horizontal one SH = 10.2 dm^2. The increasing of the surface area in this way, the intensity of electric discharge cavitation increases by 1.7–1.9 times.

The growth of cavitation intensity with increasing surface area of the liquid in the working chamber opens up wide possibilities for adapting cavitation phenomena caused by an electric discharge to the conditions of various chemical-technological processes. A similar phenomenon was observed by the authors (Enhong et al., 2024), considering hydrodynamic cavitation reactors. The authors believe that this feature is an advantage of hydrodynamic cavitation compared to ultrasonic cavitation. Since electric discharge cavitation has many advantages compared to ultrasonic one, the possibility of scaling the intensity of cavitation processes by such a simple design technique as increasing the surface area of the liquid in the working chamber is an important practical advantage of the method.

The closest to the electric discharge cavitation method in terms of its effect on biological

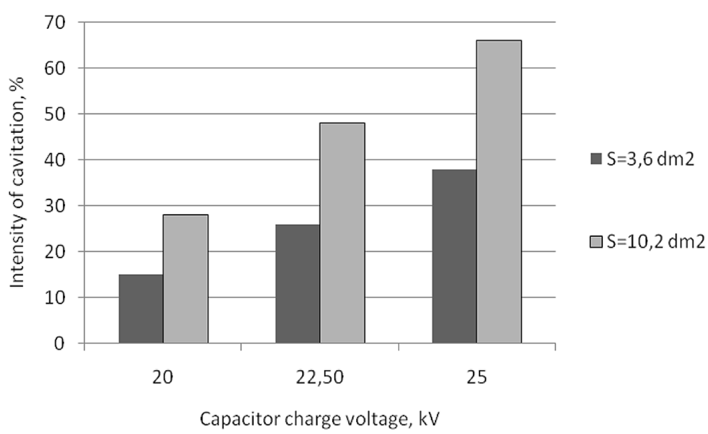

Figure 5. Dependence of the intensity of electric discharge cavitation on the surface area of the liquid in the working chamber

objects, is the method of water disinfection with ultrasound. As shown in authors' previous work (Malyushevskaya et al., 2023), the power of electric discharge cavitation is an order of magnitude higher than cavitation from any source of ultrasound for water purification. In addition, the range of acoustic vibrations caused by electric discharge cavitation in liquid extends to an area inaccessible to standard ultrasonic washers. As a result, the number of active oxidizers that ensure water disinfection is much higher for electric discharge cavitation. A separate aspect of the practical use of this method is to determine the influence of the chemical composition of the solution on the effectiveness of disinfection using this method. Also, due to the high power of the electric discharge cavitation source, the capacity of the disinfector can be easily adapted to the needs of the cleaning object.

The obtained data allow formulating technical specifications for the introduction of electric discharge in cavitation mode into various chemical-technological processes for their intensification.

CONCLUSIONS

The schemes of charge-discharge of capacitive energy storage devices, which exclude electric breakdown of liquid, and, consequently, generation of electric discharge cavitation at the final stage of discharge, are revealed. The use of such schemes of charge-discharge of capacitive storage devices of pulse current generators is unacceptable for providing special cavitation modes of discharges.

The electric scheme of capacitive energy storage devices charging electric discharge installations is proposed, allowing safely obtaining the satisfactory intensity of cavitation in a special mode of electric discharge (Scheme 3).

The dependence of the intensity of electric discharge cavitation on design features of the technological part of the installation: working chamber and electrode system is shown. The use of an electrode system with a movable plain electrode-cathode allows increasing the intensity of cavitation. Increasing the level of liquid above the electrode system leads to a decrease in the intensity of cavitation, and increasing of surface area of liquid in the working chamber allows increasing the intensity of cavitation significantly.

The obtained results open up practical prospects for the use of electric discharge cavitation in the conditions of industrial chemical-technological processes.

The research demonstrates that optimizing electric discharge cavitation processes aligns with the principles of green solutions for environmental safety, providing effective and sustainable approaches for industrial applications, such as water treatment, material processing, and chemical-technological processes.

REFERENCES

1. Anuntagool, J.; Srangsomjit, N.; Thaweewong, P.; Alvarez, G. (2023). A review on dielectric barrier discharge nonthermal plasma generation, factors affecting reactive species, and microbial inactivation. *Food Control*, *153*, 109913, https://doi.org/10.1016/j.foodcont.2023.109913
2. Bereka, V.; Boshko, I.; Kondratenko, I.; Zabulonov, Y.; Charnyi, D.; Onanko, Y.; Krasnoholovets, V. (2020). Efficiency of plasma treatment of water contaminated with persistent organic molecules. *Journal of Environmental Engineering and Science*, *16*(1), 40–47, https://doi.org/10.1680/jenes.20.00028
3. Bernatska, N.; Dzhumelia, E.; Dyakiv, V.; Mitryasova, O.; Salamon, I. (2023). Web-based information and analytical monitoring system tools–online visualization and analysis of surface water quality of mining and chemical enterprises, *Ecological Engineering & Environmental Technology*, *24*(3), 99–108.
4. Enhong, L.; Xi, Yu.; Kexin, X.; Zhewen Shao, Feng, H.; Yingping, H. (2024). Research progress of hydrodynamic cavitation reactors in the field of water treatment: A review, *Journal of Water Process Engineering*, *66*, 105997, https://doi.org/10.1016/j.jwpe.2024.105997
5. Gray, N.F. (2014). Ozone Disinfection. Editor(s): Percival, S.L., Yates, M.V., Williams, D.W., Chalmers, R.M., Gray, N.F. *Microbiology of Waterborne Diseases* (Second Edition), Academic Press, 2014, 599–615, https://doi.org/10.1016/B978-0-12-415846-7.00033-0
6. Fernandes, J.; Ramísio, P.; Puga, H. (2024). Unveiling acoustic cavitation characterization in opaque chambers through a low-cost piezoelectric sensor approach. *Electronics*, *13*(8), 1581, https://doi.org/10.3390/electronics13081581
7. Foster, J. E. (2017). Plasma-based water purification: Challenges and prospects for the future. *Phys. Plasmas*, *24*, 055501. https://doi.org/10.1063/1.4977921
8. Kosenkov, V.M. (2014). Application of circular membranes to determine the mechanical efficiency of an electric discharge in water. *Surf. Engin. Appl.*

Electrochem., *50*, 183–193, https://doi.org/10.3103/S1068375514020070

9. Malyushevskaya, A.; Koszelnik, P.; Yushchishina, A.; Mitryasova, O.; Gruca-Rokosz, R. (2022). Green approach to intensify the extraction processes of substances from plant materials. *Journal of Ecological Engineering*, *23*(7), 197–204, https://doi.org/10.12911/22998993/150060
10. Malyushevskaya, A.; Koszelnik, P.; Yushchishina, A.; Mitryasova, O.; Mats, A.; Gruca-Rokosz, R. (2023). Eco-friendly principles on the extraction of humic acids intensification from biosubstrates. *Journal of Ecological Engineering*, *24*(2), 317‒327, https://doi.org10.12911/22998993/156867
11. Malyushevskaya, A.P.; Koszelnik P.; Yushchishina, A.; Mitryasova O.; Mats A.; Gruca-Rokosz R. (2023). Synergy effect during water treatment by electric discharge and chlorination. *Environments*, *10*(6), 93, https://doi.org/10.3390/environments10060093
12. Malyushevskaya, A.; Koszelnik, P.; Mitryasova, O.; Yushchishina, A.; Mats, A.; Papciak, D.; Zdeb, M.M. (2024). Hybrid water disinfection process using electrical discharges. *Processes*, *12*(9), 1846; https://doi.org/10.3390/pr12091846
13. Mazhar, M.A.; Khan, N.A.; Ahmed, S.; Khan, A.H.; Rahisuddin, H.A.; Changani, F.; Yousefi, M.; Ahmadi Sh.; Vambol V. (2020). Chlorination disinfection by-products in municipal drinking water – A review. *Journal of Cleaner Production*, *273*, 123159, https://doi.org/10.1016/j.jclepro.2020.123159
14. Mitryasova, O.; Koszelnik, P.; Gruca-Rokosz, R.; Smyrnov, V.; Smyrnova, S.; Kida, M.; Ziembowicz, S.; Bezsonov, Ye.; Mats, A. (2021). Environmental and Geochemical parameters of bottom-sediment from the Southern Bug Estuary, *Journal of Ecological Engineering*, *22*(2), 244–255.
15. Mitryasova, O.; Cieśla, M.; Nosyk, A.; Mats, A. (2021). Hydrochemical indicators dynamic in surface water, *Journal of Ecological Engineering*, *22*(8), 111–122.
16. Moreau, M.; Orange, N.; Feuilloley, M.G.J., (2008). Non-thermal plasma technologies: New tools for bio-decontamination. *Biotechnology Advances*, *26*(6), doi.org/10.1016/j.biotechadv.2008.08.001
17. Paidalwar, A. A.; Khedikar, I. P. (2016). Overview of water disinfection by UV technology–A review. *International Journal of Science Technology & Engineering*, *2*(9), 213–https://doi.org/219.10.13140/RG.2.2.30976.25608
18. Pohrebennyk V.; Mitryasova, O.; Dzhumelia, E.; Kochanek A. (2017). Evaluation of Surface Water Quality in Mining and Chemical Industry. *17th International Multidisciplinary Scientific Geoconference SGEM 2017*, Albena, Bulgaria, 29 June – 5 July 2017, 51(17), 425–432.
19. Petrichenko, S.; Przystupa, K.; Malyushevskaya, A.; Mitryasova, O.; Kochan, O. (2024). Influence of the discharge circuit inductance on the process of galvanic wastes electrospark purification | Wpływ indukcyjności obwodu wyładowczego na proces oczyszczania odpadów galwanicznych metodą elektroiskrową. *Przeglad Elektrotechniczny*, *10*, 132–135.
20. Sato, M. (2008). Environmental and biotechnological applications of high-voltage pulsed discharges in water. *Plasma Sources Science and Technology*. *17*(2), https://doi.org/0963-0252/17/2/024021
21. Singh, R.K.; Babu, V.; Philip, L.; Ramanujam, S. (2017). *Disinfection of Water Using Pulsed Power Technique: Effect of System Parameters and Kinetic Study*. In: Sivakumar Babu, G., Saride, S., Basha, B. (eds) Sustainability Issues in Civil Engineering. Springer Transactions in Civil and Environmental Engineering. Springer, Singapore. https://doi.org/10.1007/978-981-10-1930-2_17
22. Vinnychenko, D.; Nazarova, N.; Vinnychenko, I. (2024). Development of method for frequency regulation of output current in high-voltage transformerless resonant chargers of capacitive energy storage devices. Eastern-European *Journal of Enterprise Technologies, 1*(5 (127), 6–15. https://doi.org/10.15587/1729-4061.2024.299031
23. Water Security, Issue 2: Monograph, Edited by Olena Mitryasova & Chad Staddon, Mykolaiv: PMBSNU–Bristol: UWE, 2021, 444.
24. Yushishina, A.; Malyushevsky P.; Smalko A. (2002). Iodometric determination of electric discharge volumetric cavitation. *Electronic processing of materials, 38*(2), 76‒79.
25. Zver, M.; Dobnik, D.; Zaplotnik, R.; Mozetič, M.; Filipić, A.; Primc, G. (2023). Non-thermal plasma inactivation of viruses in water solutions, *Journal of Water Process Engineering*, *53*, 103839, https://doi.org/10.1016/j.jwpe.2023.103839/