The Use of the Electrohydraulic Effect for the Disinfection of Wastewater in the Conditions of Human Habitation in Space

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UDC 628.316.6

An analysis of the existing methods of water disinfection was carried out, their advantages and disadvantages were indicated in terms of the possibility of using them in the Industrial Space Necklace "Orbit" (ISN "Orbit"). The results of tests on the disinfection of water contaminated with spore-forming bacteria *Bacillus subtilis* were presented, as well as native lake water at the UniThorr experimental electrohydraulic discharge equipment (EHDE), developed by Unitsky String Technologies Inc. The high efficiency of using the electrohydraulic discharge for disinfection was shown, which will allow switching to a reagentless method and obtaining a closed-loop water consumption cycle in the EcoCosmoHouse (ECH).

Keywords: *EcoCosmoHouse (ECH), electrohydraulic discharge, electrohydraulic discharge equipment (EHDE), electrohydraulic effect, Industrial Space Necklace "Orbit" (ISN "Orbit"), wastewater, water disinfection.*

Introduction

Purification and disinfection of water in the living conditions of people in cosmos have their own specifics, which are explained by the high cost of cargo delivery, lack of room, etc. According to the data [1], transportation of 1 kg of cargo to the International Space Station (ISS) costs 5,000–6,000 USD. In this regard, at such facilities, a mandatory requirement is the presence of a closed-loop water supply system. Thus, water regeneration at the Mir space station made it possible to reduce the cost of its delivery by about 300 mln USD per year. At the same time, despite the circular nature of the water consumption process, irretrievable water losses amounted to 7 % and were replenished only by transporting it from Earth.

To date, astronauts are allowed to consume 2.7 l of water per day to maintain their vital activity. The annual water consumption for all the needs of the space station with a crew of six people is about 9 m^3 [1]. The ISS has an implemented purification system, including distillation and iodization [2], which needs to be improved.

The Industrial Space Necklace "Orbit" (ISN "Orbit") is a multiorbital transport-infrastructural and industrial-residential complex, encompassing the planet in the equatorial plane. Created in space to serve terrestrial humanity, it will become a functional equivalent of an Equatorial Linear City, as well as a base for protection against space threats (including meteoroids) and a technological platform for the expansion of terrestrial civilization into deep space [3–5].

The EcoCosmoHouse (ECH) is an integral part of the residential and industrial infrastructure of the ISN "Orbit". The ECH is an enclosed ecosystem of the biospheric type, in which all inhabitants must not only receive a balanced diet, but also be provided with safe drinking water that meets the most stringent hygienic requirements and standards [5–7]. Under such conditions, there is an acute need to create an effective closed-loop system of water disposal, water purification and then water supply to the inhabitants of the ECH with high-quality drinking water [8, 9].

Currently, chemical (reagent), physical, as well as complex methods of disinfection are used. Note that the location of the ISN "Orbit" makes it difficult to deliver chemicals, antimicrobials, antiseptics, so the most preferred ways to obtain good quality water can be ultraviolet radiation and electrohydraulic discharge.

An effective alternative to traditional methods of disinfection in the process of developing a closed-loop purification system intended for implementation in the ECH and its terrestrial counterpart EcoCosmoHouse on Planet Earth (ECH-Earth) will be the use of an electrohydraulic discharge equipment (EHDE). Its mode of operation is based on the electrohydraulic effect (Yutkin effect) [10], the essence of which is the creation of intentional ultra-high hydraulic pressure, leading to the death even of *Bacillus anthraci* spores, the infectious agents of anthrax [11].

Analysis of Disinfection Methods

The choice of one or another method of disinfection depends on the type of water, its volume, further purpose after purification and the concentration of pollutants. The following methods are most common on Earth:

- chemical (use of various reagents and oxidizers – chlorine, chlorine dioxide, sodium hypochlorite, etc.);
- physical (heat treatment, ultraviolet radiation, exposure to ultrasound, electric discharge, etc.);
- combined (physico-chemical).

The principle of disinfection using strong oxidizers, for example, active ions of halogen derivatives, is based on their introduction into the cell shell of microorganisms, penetration and destruction of its structure. This method is used at stations of centralized water supply of settlements. However, it is ineffective against Giardia cysts. In addition, oxidizers lead to the formation of carcinogens and toxic substances. The main disadvantage of this disinfection technique is the presence of residual chlorine in drinking water, which is dangerous for humans.

Under the conditions of the ISN "Orbit", this method should not be used due to the danger of cylinder leakage, the high volatility of chlorine, as well as the need for regular delivery of reagents and oxidizers into orbit.

In space, the use of hydrogen peroxide is also impractical. The main mechanism of its bactericidal action is the formation of superoxide and hydroxyl radicals, which can have either a direct cytotoxic effect or an indirect one, leading to damage to DNA molecules, and later to the death of the bacterial cell. These radicals have a greater bactericidal effect than the original hydrogen peroxide. The disadvantages of this method include the importance of maintaining a constant temperature. So, its decrease from 18–20 °C down to 1–4 °C negatively affects the activity of hydrogen peroxide, especially in case of massive contamination of water by microorganisms [12].

The use of ultraviolet rays (recommended wavelength range 200–280 nm) for disinfecting water to drinking quality has recently gained popularity due to the fact that this method is effective against most viruses and bacteria, including cholera and typhoid pathogens, hepatitis and influenza viruses, dysentery bacilli, *Escherichia coli*. The UV spectrum coincides with the DNA absorption spectrum (λ_{max} = 260 nm), breaking hydrogen bonds between complementary DNA strands and forming dimers in the DNA molecule, and uracil hydroxylation in RNA. As a result, the process of DNA replication is hindered, which causes cell death. The longer exposure to UV light, the greater the damage. The average dose of such radiation exposure at water disinfection stations being commissioned and planned in the USA, Canada, Great Britain and France is 50–100 mJ/cm^2 [13]. This physical method has a number of advantages: high efficiency, preservation of the taste of water, no need to use reagents. However, there are a number of disadvantages: strict requirements for the degree of transparency of the medium (in terms of turbidity), the complexity of the design when used as industrial disinfection units, the impossibility of long-term storage due to the risk of re-contamination. It is worth noting that when applying UV radiation, a careful selection of the dose is necessary to prevent the appearance of any toxic by-products in the water. This is due to the fact that the disinfection effect is achieved at much lower doses of bactericidal radiation compared to the photochemical transformation of dissolved organic substances. The use of UV radiation in the living conditions of people in Earth orbit is difficult due to the need for regular delivery of lamps for replacement (every 8,000–12,000 h of operation), as well as due to the difficulties associated with the process of their disposal [13].

The methods based on changing the properties of an object due to the impact of high-voltage electric fields on it may include ozonation and the use of the electrohydraulic discharge effect.

Ozone is obtained when a silent electric discharge is applied to oxygen in special ozonator devices. Electrosynthesis of ozone is carried out in a generator, which is an emitter consisting of two electrodes separated by a dielectric. Oxidative ability is based on the destruction of cell membranes and walls, the effect on the redox system of bacteria and their protoplasm. However, when using ozone, technical and environmental problems arise: the need for large production areas, a separate building, powerful ventilation in the room; stiff requirements for the qualification of service personnel; toxicity, explosiveness.

Electric purification methods seem to be the most promising. Their essence lies in the conversion of electrical energy into other types that affect the purification object. Electrowave methods use electromagnetic energy of various frequencies, such as microwave processing, laser or ultrasonic treatment. Electrostatic methods use the energy of high voltage electrical fields, and in particular electrohydraulic shock, based on the electrohydraulic effect [10]. A number of works have shown the effectiveness of the EHDE for purifying livestock waste from pathogenic microflora [10, 11, 14], ballast wastewater disposed into the marine environment [15, 16].

Electrohydraulic discharge in water caused by electric pulses of short duration (several microseconds) at high instantaneous power (50–1,000 MW), gives rise to active free radicals, atomic oxygen and hydrogen, nitrogen compounds and the simplest amino acids. The process is facilitated by air and other gases dissolved in water. Microbial flora, first of all bacterial, dies heavily, which is associated with ultrasonic, ultraviolet and X-ray radiation of the discharge channel plasma, as well as with a powerful oxidizing effect of atomic oxygen [17].

The authors [10, 18, 19] consider ultraviolet radiation and ultrasound generated by an electrohydraulic discharge to be the dominant disinfecting factors in the EHDE, rather than thermal shock, ultrahigh hydraulic pressure or chemicals. However, it is stated in [20] that it is the shock wave generated during the formation of the plasma channel that is the most important factor responsible for the inactivation of microorganisms, while the effect of UV radiation, chemical oxidizers and pulsed electric fields is insignificant. It was also shown in [21, 22] that the bacterial cell wall is damaged by the shock wave generated by the pulsed discharge plasma.

Obviously, when disinfecting water with an electrohydraulic discharge, a complex of factors leads to the death of microflora, depending on the type/strain of the microorganism. The liquid treated in this way acquires bactericidal properties that do not decrease over time. Disinfection is very intensive, and the speed of the process is proportional to the number and energy of pulses that cause electrohydraulic discharges [23].

One of the main advantages of using electrohydraulic discharge technologies in space life is environmental friendliness, which is dictated by the absence of chemicals and by-products. In addition, the presence of solar energy allows getting cheap electricity in sufficient quantities to power the water purification system.

The safety of drinking water in an epidemic sense is determined by the absence of pathogenic bacteria, viruses and protozoa in it, its compliance with the standards for microbiological and parasitological indicators [23]. The literature describes studies on the effect of electrohydraulic discharge on various non-spore-forming microorganisms, including the intestinal bacteria group, the main representative of which is *Escherichia coli* [18, 19, 24, 25]. However, bacteria that have the ability to sporulate, upon the onset of unfavorable conditions for life, form a dense shell under the outer membrane.

In this case, spores are not a method of bacteria reproduction; at the same time, the reduced volume due to the partial loss of water allows them to survive and spread more efficiently. Spores can be dormant for a long time and are characterized by a low level of metabolic activity distinguished by an unusually high heat resistance, maintaining their viability when boiled for several hours, as well as increased resistance to ultraviolet radiation and mechanical stress. In view of the foregoing, it can be concluded that the use of electrohydraulic discharge is relevant for the disinfection of water, also if it contains spore-forming microorganisms.

The purpose of this work is to study the effect of electrohydraulic discharge on the death of spore-forming microorganisms using the *Bacillus subtilis* (*B. subtilis*) testing culture as an example.

According to the purpose, the following tasks were solved:

- determination of the effect of electrohydraulic discharge on the death of microorganisms;
- establishing the dependence of the degree of disinfection on the treatment time and the initial concentration of microorganism cells in the solution.

Materials and Methods of Research

Gram-positive spore-forming soil bacterium *B. subtilis* strain G BKM B-911 was chosen as the object of study (Figure 1). It was taken from the own bank of microorganisms of the Biotechnology Department laboratory of Unitsky String Technologies Inc. [5].

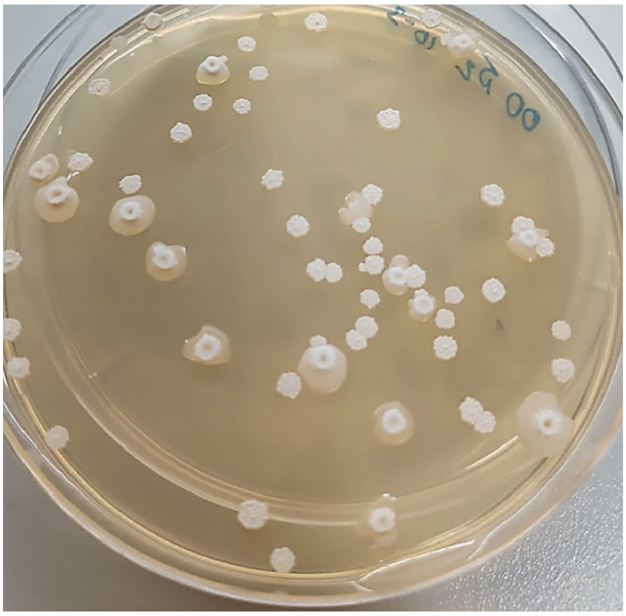


Figure 1 – Growth of *B. subtilis* colonies in a Petri dish

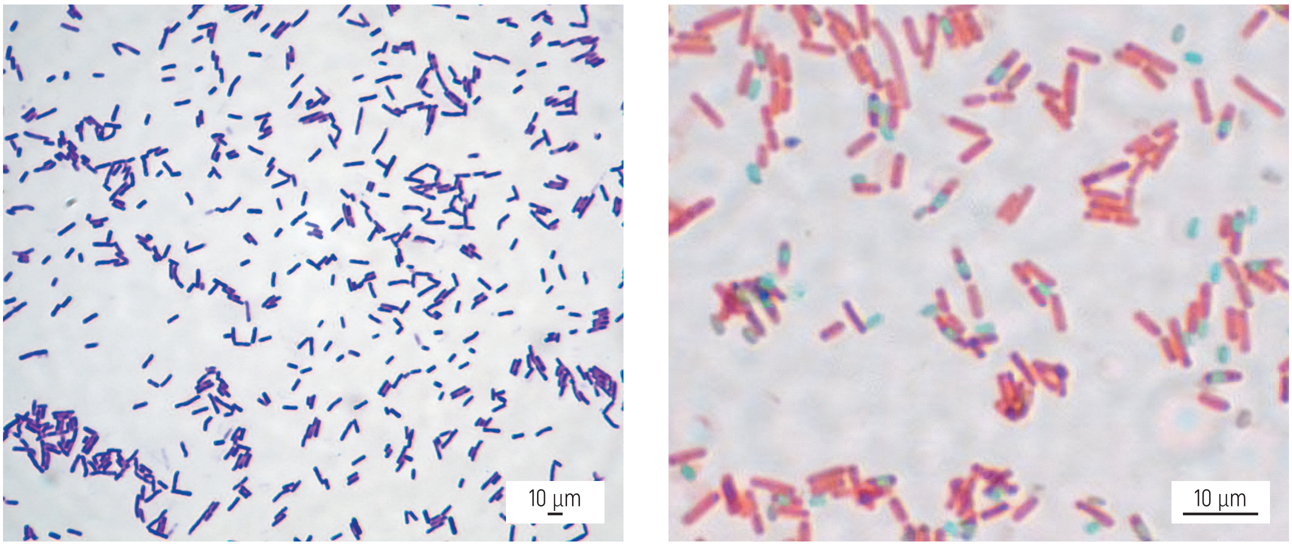
B. subtilis, or hay bacterium, a microorganism inhabiting the soil, the intestines of animals and humans, as well as occurring in water and air, is one of the most studied representatives of the genus *Bacillus*, which can form spores or endospores located in the central part of the mother cell and having an oval shape with a multilayer hard-to-penetrate shell.

As a rule, the studied inoculum of microorganisms contains spores, vegetative cells and vegetative cells with endospores in various proportions (Figure 2). When negatively affected, vegetative cells are the least resistant, and spores are the most viable; therefore, aged 3–4-day cultures were used for the experiment (during such a period, bacteria, presumably, pass through all stages of development).

The effectiveness of the use of electrohydraulic discharge, implemented in the UniThorr EHDE (developed by the Test Equipment design bureau of Unitsky String Technologies Inc.), was studied in water artificially contaminated with spore-forming microorganisms up to a concentration that corresponds to the content of bacteria in wastewater.

The production of the inoculum of the testing culture *B. subtilis* strain G BKM B-911 was carried out in the Biotechnology Department laboratory using the periodic method [26].

The culture fluid with different initial concentrations of microorganisms was subjected to electrohydraulic discharge in the time interval from 6 s to 40 min; pulse energy – 400 kJ. The EHDE operation parameters: voltage – 45 kV, current – 15 kA, charging circuit capacity – 0.4 μF, working chamber volume – 9 l. Water sampling before and after exposure was performed aseptically. The repetition rate of each sample was equal to three. Seeding on the surface of a dense agar medium was carried out by the Koch method, followed by incubation, after which the colonies grown on nutrient agar were counted [26]. The degree of water disinfection was estimated by the change in the number of colony-forming units (CFU) as a result



a) b)

Figure 2 – *B. subtilis* microorganisms stained with methylene blue solution:
a – as per the Loeffler method; b – as per the Peshkov method (vegetative cells are red, spores are green/blue)

of exposure to the EHDE. The total number of microorganisms in the initial samples was in the range of 10^4–10^5 CFU per 1 ml of solution.

Next, we studied lake water sampled in the Aquarelle EcoPark (Maryina Gorka, Belarus). This artificially created water reservoir was chosen as the most likely prototype of a secluded aquatic ecosystem.

Obtained Results

Experiments to determine the effect of electrohydraulic discharge on the death of microorganisms of the selected testing culture with a concentration of 4.5×10^5 CFU/ml, carried out at the UniThorr EHDE, revealed a decrease in total microbial count (TMC) by one order of magnitude after 10 min of exposure. An increase in the operating time of the EHDE to 40 min leads to a decrease in TMC by 99 %, but does not allow to achieve a complete destruction of microorganisms (Figure 3).

At a higher initial concentration of microorganisms in the solution – 4.5×10^5 CFU/ml – an intense disinfecting effect is observed with an exposure time of up to 10 min, then the dependence of TMC on the treatment time is linear (Figure 3). In the interval from the 10th to the 15th min of treatment, the TMC value increases, and then its further decrease is noted. This phenomenon can be explained

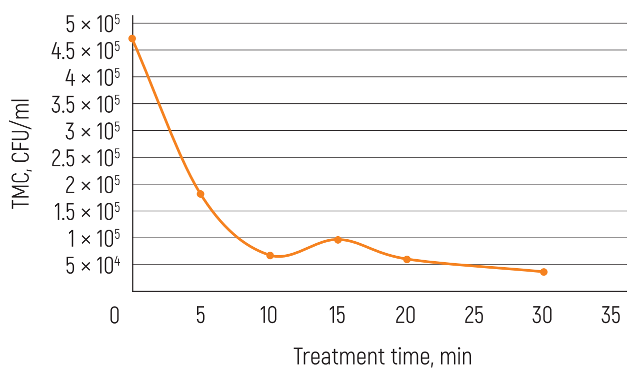


Figure 3 – Influence of treatment time on TMC
at the initial concentration of microorganisms of 4.5×10^5 CFU/ml

by the so-called bacterial explosion effect. The possibility of its occurrence is described in [10]. This phenomenon is due to the fact that the weakest microorganisms are initially destroyed and those most resistant to external factors remain in the solution. In addition, during electrohydraulic discharge, the content of nitrogen compounds and other nutrients in the water medium increases. After the EHDE operation is stopped and in the presence of nutrients (including nitrogen), a rapid growth of the surviving and strongest representatives of the bacterial colony occurs.

The residual value of TMC during electrohydraulic discharge treatment of contaminated water with the initial concentration of microorganisms of 5.5 × 10⁴ CFU/ml is less than 50 CFU/ml, which meets the requirements of sanitary rules and norms [23] for the quality of drinking water by this indicator. However, a less pronounced effect of the bacterial explosion was noted at the 10th min of treatment (Figure 4).

A decrease in the initial concentration of microorganisms from 5.5×10^4 CFU/ml to 3×10^3 CFU/ml showed that the most intense disinfecting effect is observed already during the first 5 min of treatment (Figure 4).

In further experiments, the repeatability of the results obtained was confirmed, the time range was narrowed, and the influence of the minimum exposure time on the TMC of water was studied. Fixed reference points were determined: 6 s and 10 s. The nature of the dependence of TMC on the treatment time coincided (Figure 5) except the points when the operating time of the EHDE was 6 s and 10 s. It was revealed that it is during the first 6–10 s up to 94 % of microorganisms are destroyed (Figure 5).

Taking into account the data obtained, the dependence of TMC on the treatment time was conditionally divided into three sections (Figure 6).

Section I, lasting up to 10 s, is characterized by a sharp decrease in TMC from 3×10^4 CFU/ml to 2×10^3 CFU/ml, which is up to 93 %. It is assumed that the death of predominantly vegetative cells occurs in this area, as they are the least resistant to the effects of electrohydraulic discharge. In section II, lasting from 10 s to 15 min, there is a decrease in TMC values from 2×10^3 CFU/ml to 1×10^2 CFU/ml, which is probably associated with the death of vegetative cells with endospores. Section III of the dependence of TMC on time, which begins after 15 min, has a linear, almost horizontal shape. A slight decrease in TMC at the last stage is probably caused by the destruction of spores remaining in the water medium, which have a dense shell and tolerate adverse environmental conditions well.

The complex nature of such a disinfection method as electrohydraulic discharge is especially important when purifying waters containing a wide range of microorganisms. In this regard, further research was carried out on the effect of treating native lake water at the UniThorr EHDE. The obtained data (Figure 7) identical to the results of treatment of water contaminated with *B. subtilis* (Figures 3, 4). The efficiency of lake water disinfection was 99 %. The residual value of TMC after treatment at the UniThorr EHDE is 75 CFU/ml. However, despite the high efficiency of treatment, the required indicators of drinking water were not achieved (the standard according to sanitary rules and norms is no more than 50 CFU/ml) [23].

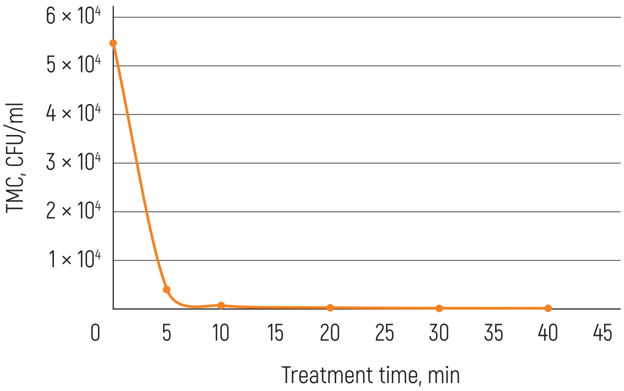


Figure 4 – Influence of treatment time on TMC
at the initial concentration of microorganisms of 5.5×10^4 CFU/ml

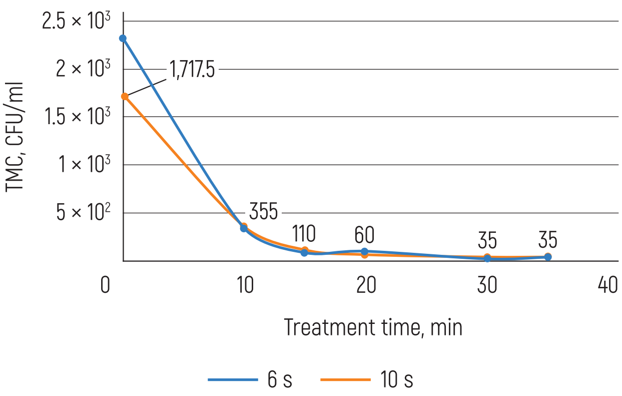


Figure 5 – Influence of treatment time on TMC
at the initial concentration of microorganisms of 3×10^4 CFU/ml

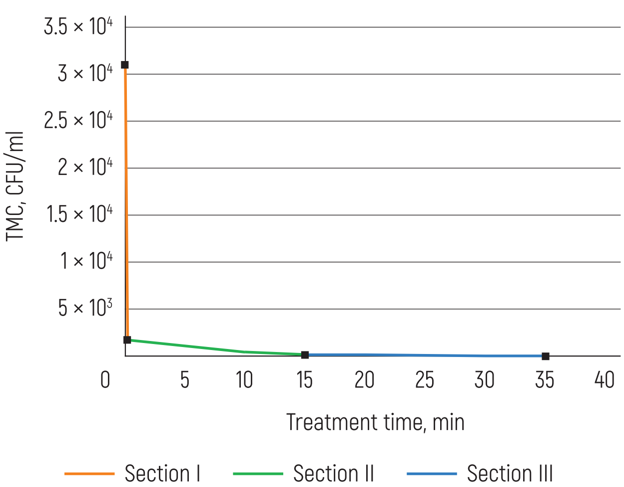


Figure 6 – Influence of treatment time on TMC
at the initial concentration of microorganisms of 3×10^4 CFU/ml
with the division of the graphic chart into sections (I, II, III)

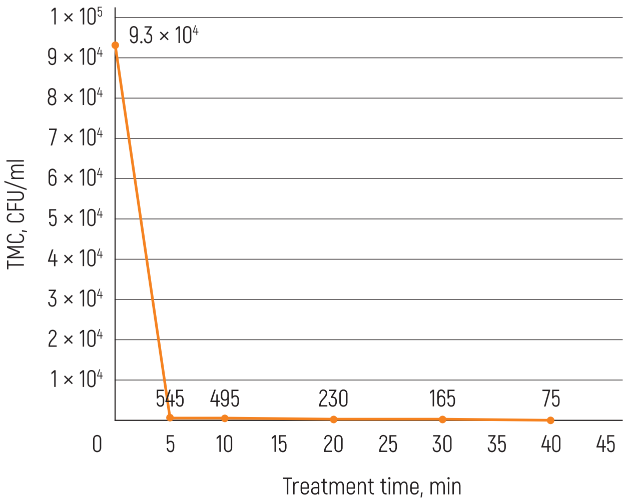


Figure 7 – Influence of treatment time on TMC of lake water

In accordance with [23], which establish the requirements for the quality of water in centralized drinking water supply systems, control is carried out according to the following microbiological indicators: the total microbial count, the content of common thermotolerant and coliform bacteria, spores of sulfite-reducing bacteria, coliphages and Giardia cysts. In addition, drinking water should not contain viruses and protozoa. In this regard, it is advisable to expand studies on the influence of the electrohydraulic discharge on these indicators.

The results of the experiments carried out show that the use of electrohydraulic discharge can reduce biological pollution.

Conclusions and Future Work

This article reflects the problem of limited water resources for people in the conditions of being in space. An assessment is given to the best existing methods of water disinfection, taking into account the possibility of their use in the ISN "Orbit", their advantages and disadvantages are shown.

The possibility of using the UniThorr EHDE for water disinfection was studied (by the examples of native lake water and water artificially contaminated with the *B. subtilis* strain) and the high efficiency of this method was confirmed (the degree of disinfection reached 99 %). Note that disinfection for 40 min of water containing spore-forming bacteria at a concentration of 5.5×10^4 CFU/ml made it possible to achieve the quality of drinking water as per TMC.

The conducted microbiological studies have revealed a significant decrease in the bacterial contamination of wastewater under the influence of electrohydraulic discharge, which indicates a high degree of disinfection. Further work will be aimed at increasing the efficiency of purification using the EHDE, as well as studying changes in the microbiological contamination of waste, river and other water in terms of microbiological and parasitological indicators.

Therefore, it can be concluded that it is expedient to use the UniThorr EHDE in the water purification system at the stage of water disinfection, which will make it possible to switch over to the reagentless method and obtain a closed-loop water consumption cycle in the ECH, which requires water of not only drinking, but also technical quality, as well as for irrigation of cultivated plants. In addition, the ISN "Orbit", where the most harmful industrial production will be removed to from the planet Earth in the future, will need effective water purification systems with subsequent disinfection. In this regard, on the basis of additional experiments, options for a closed-loop water purification system will be proposed, taking into account its purpose of use.

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