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Water Decontamination at Water Treatment Plants. A New Approach

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Abstract

Analysis of the chemical and physical methods of water decontamination is carried out, the advantages and shortcomings of their application are revealed. A new approach to water treatment at centralized water-preparation stations is proposed. The approach involves the treatment of natural surface water, as the source of drinking water supply, by means of air floatation using ceramic membranes, coagulation (with aluminium sulphates or hydroxochlorides), filtration (through sand filters) to prevent biofouling and to enhance the efficiency of decontamination of purified transparent water after filtration, irradiation with ultraviolet light and subsequent water conservation by carbon dioxide (to restrain the growth and propagation of microflora in the distributing network). Additional decontamination of water from the city water supply in the case of the necessity to use it for drinking purposes may be carried out by boiling. This will allow complete elimination of the chlorination of piped water and the negative effects of this kind of treatment.

Keywords: tap water preparation, treatment with UV radiation, treatment with carbon dioxide, prevention of the secondary growth of bacteria

INTRODUCTION

What is drinking water? This is not pure (distilled) water, but genetically safe, physiologically valuable water intended for everyday and unlimited use by people. Tap water cannot be drinking water in any country if this water is chlorinated. The main difference of drinking water from table and mineral water is lower mineralization.

In [1], analysis of the book written in 2013 by Michael J. McGuire "The Chlorine Revolution: Water Disinfection and the Fight to Save Lives" is given. In this book, the author discussed the development of the methods of water sanitation during the years 1890–1910. Arguments concerning chemophobia around water sanitation are considered, which are comparable with the current controversy concerning the influenza vaccine and genetically modified food. The negative health consequences of water chlorination, mainly due to the formation of trihalogenomethanes and other side products of chlorination, are well known today. However, the author reminded that cholera, typhoid fever and other diseases transferred through water had been the reasons for the death of many people. For example, in 1891 about 2000 people died of typhoid fever in Chicago because disposal lines ran directly into the main source of drinking water for the city, that is, the Chicago River. At that moment, which occurred more than a hundred years ago, water chlorination was a vital necessity in spite of the current anxiety concerning the carcinogenic side products of water chlorination. It should be stressed that so-called revolutionary scientific achievements can rarely be free from contradictions. However, the time has come when scientific developments and achievements aimed at a decrease in microbial risk and unfavourable health consequences to which the population is subjected through drinking water allow solving this problem in favour of the conservation and improvement of the health of the whole Mankind.

Water decontamination is an extremely important stage in the preparation of high-quality drinking water. This operation involves the destruction of living and pathogenic microorganisms (bacteria and viruses). It is microbiological contamination of water that occupies the leading position in the evaluation of risk for human health. It is established at present that the danger of diseases caused by pathogenic microorganisms present in water is a thousand times higher than the danger of was pollution with chemical compounds of different nature (except for ecological disasters). Because of this, decontamination to a level corresponding to the existing hygienic standards is a compulsory condition for obtaining drinking-quality water [2]. In the practice of water preparation, the methods of water decontamination are conventionally divided into reagent-based (chemical), reagent-free (physical) and combined.

Upgrading of water preparation facilities for the purpose of increasing the quality and safety of drinking water is carried out periodically all over the world. In particular, some principal changes are introduced because of technogenic catastrophes. For example, after the disaster in Chernobyl, radiation control and temporary filtration through zeolite charge was introduced to absorb radionuclides. However, water decontamination by means of chlorination remains unchanged for more than 150 years. Water chlorination at large water pipe stations is carried out mainly with gaseous chlorine or the substances containing so-called active chlorine (chloride lime, hypochlorites, chloroamines, chlorine dioxide, a mixture of oxidants, *etc.*). Chloroorganic compounds formed during chlorination are very dangerous for human health. Because of this, water from centralized water supply treated with chlorine (chlorinated) cannot be related to drinking water. The society has already recognized the problem of drinking water quality, which had long ago become not only national but global. In this connection, a problem of high priority in the preparation of drinking water is the search and hygienic evaluation of new, alternative and additional methods of water purification, including decontamination.

In the present work, an analysis of the chemical and physical methods of water decontamination is presented, the advantages and shortcomings of their use are revealed, and a new approach to the technology of centralized water preparation at water-pumping enterprises is proposed.

CHEMICAL METHODS OF WATER DECONTAMINATION

Treatment with chlorine-containing compounds

It is known [2] that water of centralized water supply not only in Ukraine but in many countries is chlorinated for disinfection: river water is treated with chlorine twice – immediately after water intake and before supplying it into the pipeline, while water from underground sources is treated only before supplying into the water pipeline.

An optimal dose of chlorine, active one (free) for the elimination of microorganisms and residual (bound) for reliable disinfection (for the complete bactericidal effect) in tap water is 0.8–1.2 and 0.3–0.5 mg/L, respectively. The necessity to normalize these doses is due to the fact that the presence of residual chlorine in the amount less than 0.3 mg/L may be insufficient for water disinfection, while at doses above 0.5 mg/L water has an unpleasant specific chlorine odour. he advantages of the indicated method of disinfection based on chlorine include good solubility of chlorine and chlorine-containing compounds in water, the ability of these compounds to remain active in the moving medium, disinfecting action on the inner walls of pipelines, economic profitability of this reagent for disinfection of large water volumes.

In [3], on the basis of a comparative analysis of all widely used disinfectants, the importance of chlorination for the provision of the epidemiological safety of water is convincingly proven, at least for the final stage of water preparation before supplying it into the reservoir of pure water. Only in the case of organic compounds are present in water, the use of chlorine is excluded during primary disinfection due to the danger of the formation of halogenated compounds causing negative health effects. In the opinion of the authors, many experts consider water chlorination as the most essential invention in medicine in the XX century that had brought the greatest benefit to people.

The features of the action of chloroorganic agents used for water decontamination are to be considered in more detail.

Chlorine (Cl_2) is a toxic green-yellow gas with a sharp damp odour, heavier than air by a factor of 2.45; chlorine solubility in water increases with a decrease in temperature and an increase in pressure. Chlorine handling facilities are of potential high ecological risk with large-scale lethal consequences.

Liquid chlorine supplied to the water-treatment facilities in tanks or cylinders is transformed into the gas state before application. This procedure is carried out in special chlorinating installations providing automatic gas supply and dosing. Chlorination with liquid chlorine is still the most widespread method of water disinfection at medium and large water purification stations in many countries. When introduced into water, chlorine undergoes hydrolysis:

$Cl_2 + H_2O = HClO + HCl$

A part of hypochlorous acid (HClO) dissociates with the formation of hypochlorite ion OCl^-. In the case if ammonia is present in water (water ammonization is often used specially for this purpose), mono- (NH_2Cl) and dichloroamines ($NHCl_2$) are formed:

$HClO + NH_3 = NH_2Cl + H_2O$

$HClO + NH_2Cl = NHCl_2 + H_2O$

Active chlorine is the term related to the major disinfectant species Cl_2, HClO, OCl^-, NH_2Cl and $NHCl_2$; free chlorine is the term related to Cl_2, HClO and OCl^-, while NH_2Cl and $NHCl_2$ are termed as bound chlorine. Chlorination has several advantages: first, this process allows not only water purification from undesirable organic and biological impurities but also a complete removal of dissolved iron and manganese salts; second, it ensures microbiological safety of water during its transportation to consumers due to aftereffect. The aftereffect is a very important property of the use of chlorine. If chlorine is taken in some calculated excess, so that after passing treatment facilities the residual amount of chlorine would be 0.3–0.5 mg/L, the secondary growth of microorganisms in water does not occur.

Shortcomings of chlorination are the necessity to work with highly toxic gas, and the presence of free chlorine in treated water, which worsens the organoleptic properties of water. However, one of the main shortcomings of the use of gaseous (liquid) chlorine as a disinfectant is the formation of side halogen-containing compounds (HCC), bromate, chlorite and other ions. The major part of HCC is composed of trihalogenomethanes (THM) – chloroform, bromodichloromethane, dibromochloromethane, bromoform, *etc.* The formation of these compounds is due to the interaction of active chlorine with organic compounds of natural origin. Free chlorine is an efficient disinfectant against bacterial and viruses; however, it is not always so efficient against *Cryptosporidium parvum* and *Giardia lamblia.* Chloroorganic compounds are characterized by high toxicity, mutagenicity and carcinogenicity. In addition, these compounds are rather stable; having passed through the water supply and sewerage system, they cause the pollution of river water downstream along with waste waters from communal facilities. The risk of diseases or even deaths from pathogenic microorganisms in drinking water is much higher than the risk of the effect of disinfectants and side products of disinfection. Nevertheless, if THM level exceeds the standard permissible level, strategies should be aimed at preliminary removal of organic impurities from water without any detriment of disinfection.

So, the use of gaseous chlorine for disinfection may cause unpredictable consequences: in the case of chlorine emission, even a single breath of this gas is sufficient for lethal termination; a great number of super-toxic compounds are formed in water, among which the most dangerous ones are chloroorganic compounds with clearly pronounced toxicity, mutagenicity, and carcinogenicity. In addition, chlorine promotes the transformation of microorganisms into mutant non-cultivated forms acquiring resistance to chlorine [2].

Decontamination of surface waters at the stations of water preparation [4] by chlorination using ammonium sulphate (ammonization) at the first stage, with repeated chlorination at the final stage of water purification before supplying it into water pipeline promotes almost a 2-fold decrease in the formation of chlorinated compounds. Unfortunately, the use of ammonium salts does not eliminate chlorinated compounds from water; ammonium ions themselves do not belong to ecologically safe reagents for drinking water.

As alternatives to chlorine, other disinfectant agents become increasingly popular, for example, **sodium hypochlorite** (NaClO), which is obtained through the electrolysis of the solutions of sodium chloride [5]. The advantages of the use of concentrated NaClO solution include a decrease in secondary contamination in comparison with the use of gaseous chlorine; the simplicity of transportation and storage without enhanced safety measures; it is possible to obtain this agent directly at the site by means of electrolysis.

The electrolytic method is characterized by low expenses and safety; the reagent is readily dosed, which allows automation of water disinfection process; a large per cent of pure active chlorine, the stability and high quality; the simplicity of the reaction and easy determination of the necessary dose; availability and undemanding storage. Shortcomings are the effects of pH and temperature at which the treatment of drinking water is carried out on the disinfectant characteristics of sodium hypochlorite. In addition, the reagents facility used in the case is rather tedious, which is connected with the necessity to store large amounts of chemicals (3–5 times more than the amount of chemicals in the case of the use of chlorine); transportation volume increases; storage is accompanied by partial decomposition of the reagents; there is still the necessity in the supply-and-exhaust ventilation system and safety measured for the personnel. In addition to the facts listed above, the solutions of chlorinated reagents are corrosion-active and require the equipment and pipelines made of stainless materials or with corrosion-proof coatings. Finally, these reagents are similar to chlorine in the ecological respect and the effect on human health.

Chlorine dioxide (ClO_2) is 10 times between soluble in water than chlorine. Chlorine molecule is able to accept two electrons in oxidation-reduction processes, while chlorine dioxide can accept five electrons. This means that ClO_2 is 2.5 times more efficient.

$$5NaClO_2 + 4HCl \rightarrow 4ClO_2 + 5NaCl + 2H_2O$$

In ClO_2 electrons are accepted by oxygen atoms, while in Cl_2 they are accepted only by chlorine atoms, and this fact explains noticeable differences in the properties of these substances. It should be specially stressed that the reaction between chlorine and organic substances leads to the addition of chlorine atoms to the molecules of the latter compounds with the formation of toxic chloroorganic compounds. Quite the contrary, chlorine dioxide gives its oxygen atoms to organic substances during the interaction, so it is less dangerous than pure chlorine.

Not only in Ukraine but also in other FSU countries chlorine dioxide relates to little-known reagents, it is a rather exotic agent of water decontamination. At first sight, this may seem strange because the advantages of this agent in comparison with other oxidizers (chlorine and ozone) are distinct, which ensures the use of this agent in many countries of the world. Chlorine dioxide is a disinfectant of non-chlorine type, and it does not form free chlorine. Due to the unique structure of ClO_2 molecule, the major reactant species is active oxygen, so chlorine dioxide is recognized as the green chemistry.

Chlorine dioxide has some advantages in comparison with chlorine:

– better organoleptic (taste, odour, colour, turbidity) characteristics of water;

– high biocide activity with respect to all forms of microorganisms including spores, viruses, cysts, protozoa, helminth eggs, micro-algae *etc.*;

– high rate of disinfection with substantially lower concentration of the substance;

– removal of microbial sediments, prevention of the formation of these sediments in water distributing network;

– the absence of the formation of chlorine-containing compounds including THM, chlorophenols, polychlorinated diphenyls etc. In the case of chlorine dioxide application, the amount of the formed THM is 1–25 % of the amount formed in the case of the treatment of the same volume of water with chlorine. Results of some studies provide evidence of the absence of chloroform formation in natural waters treated with ClO_2 in the concentration up to 1.0 mg/L;

– absence of reactions with ammonia and ammonium ions;

– independence of the oxidation-reduction potential on water pH;

– improvement of water flocculation at the initial stage of water treatment;

– ecological safety;

– long-term (up to 7 days) bacteriostatic effect in water-distributing systems and, as a consequence, removal of microbiological sediments from the pipeline system.

This later property of ClO_2 is most attractive for the purpose of substantial enhancement of the quality of drinking water supplied to consumers. Possessing long-term bactericidal effect, ClO_2 prevents secondary contamination of water in pipelines. The products of vital activity of bacteria living in pipelines account for the major fraction in the composition of pollutants entering water supply sites. Chlorine dioxide kills the bacterial over the whole length of the water-distribution network and thus purified pipelines without any substantial capital expenditure.

Within the studies of technologies that are alternative to liquid chlorine, laboratory and industrial tests of water decontamination with chlorine dioxide are carried out at the Dnepr and Desna water pipeline stations of Kievvodokanal are carried out.

The solution of a **mixed oxidant** has got its name due to a special technology of the electrolysis of sodium chloride solution providing the formation of several oxidants in one solution. This process is closer to hydrogen electrolysis and allows using a lower amount of salt and higher current, as well as a special pack of electrodes, to obtain qualitatively different disinfectant, which is much more efficient than the traditional means of water decontamination. The mixed oxidant has united almost all the advantages of such disinfectants like chlorine, sodium hypochlorite, chlorine dioxide, ozone, hydrogen peroxide, etc. This mixed oxidant is almost devoid of shortcomings characteristic of the listed oxidizers. Unlike dangerous chemicals (liquid chlorine, commercial sodium hypochlorite, *etc.*) requiring the arrangement of special safety zones for storage and causing potential danger of ecological disasters, the raw materials necessary for the mixed oxidant are only water, salt and electricity. The use of safe resources and the provision of production safety appear to be the most urgent question with respect to water purification facilities. The production of the mixed oxidant at the consumption site in the necessary amounts excludes the transportation of dangerous substances, which causes a decrease in transportation costs and the costs for the provision of safe transportation. The mixed oxidant possesses stronger disinfectant characteristics than sodium hypochlorite or liquid chlorine. It is also efficient in removing and preventing the formation of biofilms on pipe walls and in pure water reservoirs. The use of the mixed oxidant for disinfection of water and sewage in the systems of centralized water supply, in swimming pools and entertaining centres, sewage purification facilities and the systems of circulating water provides the following advantages for consumers:

– the absence of the necessity to arrange safety zones for the storage of dangerous chemicals;

– a decrease in the dose of active chlorine to achieve the planned results;

– a decrease in the formation of the side products of disinfection in the treated water;

– removal of biofouling and green algae, which improves the taste and odour of water substantially;

– a decrease in the amount of preparations for preliminary purification of water;

– a decrease in the rate of tube corrosion.

In general, the advantages listed above will allow achieving substantial economic effect and a decrease in expenses for transport, interaction with controlling organs, additional preparations for water purification, service and repair of technological equipment, which ensures rapid recoupment of the equipment. A not less important question in the production of drinking water is the reliability, quality and technological reasonableness of the equipment used to manufacture sodium hypochlorite or the mixed oxidant.

Chloramines (NH_2Cl, $NHCl_2$) are less efficient chlorine-containing reagents and are not recommended for use as the major disinfectants. Chloramines are preferable for the secondary disinfection of water because they react slower than chlorine and are more stable in water-distributing systems.

New technologies of reagent disinfection

Substantial disadvantages and the inability of traditional purification processes to eliminate pathogenic organisms causing danger for life require the development of improved and/or new disinfection technologies.

A new reagent that has been recently proposed for water treatment is **aquaton**. Its action is integrated, and its active substance is a biocide guanidine high-molecule polymer polyhexamethyleneguanidine hydrochloride (PHMG) (manufactured by STC UKRVODBEZPEKA) [6]. The advantages of this preparation include high efficiency, prolonged action, a broad range of antimicrobial action. However, it also has some shortcomings: the absence of unambiguous warranty of remote consequences of long-term application for drinking water supply; initial (threshold) signs of the toxic effect of PHMG manifest themselves at very low concentration (0.4 mg/k), which is only 2.2 times higher than the minimal disinfecting concentration (0.18 mg/L). Lower PHMG concentrations are ineffective.

It was demonstrated [7] that **nanotechnologies** may propose solutions in the area of disinfection due to the use of nanosorbents, nanocatalysts, bioactive nanoparticles, nanostructured catalytic membranes and filtration involving nanoparticles. However, these proposals of the authors did not develop in practice, and the search for the methods of water quality improvement is still going on.

In [8], a review of the modern level of knowledge is presented, describing the use of advances **oxidative technologies** (ozone, Fenton reagent, ultraviolet (UV) treatment, photocatalysis, hydrogen peroxide) to disinfect water, to remove the compounds causing worsening of taste and odour, first of all, benzothiazoles, mercaptanes and sulphides, as well as aromatic and other compounds.

The authors of [9] compared disinfection of drinking water with chlorine dioxide at low initial concentrations (0.05–0.1 mg/L) through the example of the level of adenovirus and demonstrated that this method is the main stage of decontamination, while UV treatment of water at a dose of 40 and even 73 mJ/cm^2 without disinfection with chlorine dioxide was insufficient.

In [10], the contribution from each stage of water treatment including ion exchange in the suspended bed, ozonation, coagulation, ceramic microfiltration and filtration through granulated active coal is evaluated. Chlorination was carried out on the laboratory scale after each stage of the process to investigate the effect of each kind of treatment on the formation of the side products of disinfection. A correlation between the content of the aromatic component of natural organic compounds and the amount of the side products of disinfection was discovered. It was demonstrated that the high doses of chlorination of raw water caused genotoxicity, which decreased at every next stage of water treatment.

A critical analysis of the selection of water purification and disinfection methods was presented in [11]. It was revealed that tighter restrictions posed by the Environmental Protection Agency of the USA (USEPA) on the limits for some side products of water disinfection forced water supply enterprises to pass from the usual disinfecting agent (chlorination) to alternative ones. Nevertheless, the use of alternative disinfectants causes the formation of new kinds of products known as uncontrolled products, which may be even more toxic in many cases. The number of these most important identified compounds was estimated to be nine groups and 36 kinds, including halogenated acetonitriles and acetaldehydes. The results may help water supply organizations to choose water purification processes for the purpose of decreasing the risk for human health.

Industrial and urban activities are accompanied by the formation of large amounts of polluted groundwaters, which bring a serious problem for health worldwide. Infectious diseases are the most widespread risk for health connected with drinking water, and waste water purification is the major concern of our modern society. The area of water purification is replenished with new nano-sized devices for water decontamination, which surpass the majority of technologies available at present. In particular, magnetic nanoparticles (MNP) of iron oxide are widely used in the environment due to their unique physicochemical properties. The authors of [12] demonstrated the possibility to use MNP coated with polyethylene glycol and functionalized with an antimicrobial peptide to obtain a new magnetically sensitive support with antimicrobial activity through the example of *Escherichia coli* K-12 DSM498 and *Bacillus subtilis* 168. It was established that **magnetically sensitive antimicrobial device** may be successfully used for water disinfection. The minimal inhibiting concentration (500 μmol/L) with the visible bactericidal effect for both strains was determined with the help of the platform of rapid highly productive screening.

Water disinfection with **ozone** is technically the most complicated and rather expensive method of water treatment. Ozone is the most efficient disinfectant to inactivate bacteria, viruses and protozoa. However, water should not contain bromide ions [13, 14] because bromate ions formed in this method of treatment are highly toxic (their maximum permissible concentration (MPC) is 10 μg/L according to the standard for drinking water) [15]. Ozone itself is toxic, too: the maximum permissible concentration of this gas in the air of industrial facilities is 0.1 g/m^3, in addition, there is a danger of explosion of ozone-air mixture. It should be stressed that, though a number of foreign companies propose autonomous ozonation installations for the water supply of a separate cottage or for water purification in a swimming pool, the cost of these devices is very high, and they require service skilled service personnel.

The use of **heavy metals** (copper, silver, *etc.*) for disinfection of drinking water is based on the use of their oligodynamic property, that is, the ability to cause bactericidal action in small concentrations. These metals may be introduced in the form of salt solutions or by means of electrochemical dissolution. In both cases, an indirect control of their content in water is possible. It should be stressed that the MPC of silver and copper ions in drinking water are rather tight, and requirements to water disposed into fishery water reservoirs are even tighter. These heavy metals are toxic also for humans. Occasional use of water disinfected with silver ions does not bring immediate harm to human health, but longer use is extremely dangerous and brings the risk of argyrosis. In addition, skin state changes, it becomes bluish, and its elasticity decreases. It was proven that the method of water disinfection with the help for silver ions may cause various mutations, promotes DNA destruction, and this has consequences for human health in general and results in irreversible consequences. Water disinfection with silver was also used on ocean ships. Satisfactory bactericidal characteristics with relatively low rate of the material consumption was demonstrated by the authors of [16] through the example of the composite granules of alginate from silver nanoparticles synthesized *via* three different approaches and used as fillers in the columns for simultaneous filtration and disinfection as the alternative process of water purification. The prepared composite balls were packed in the column through which water containing *E. coli* was filtered to evaluate the efficiency of disinfection.

One can see that the problem of water decontamination is urgent for scientists all over the world, and some of the proposed versions may be used at local purification facilities. However, new technologies are extremely necessary. For example, only in Kiev more than 100 t of chlorine is stored at only one water purification station. This amount may be multiplied by several hundred for all water supply facilities taking into account the date of construction and capital repair works. Times change, but chlorine, being a weapon of mass destruction, is still used for water decontamination, though the use of this reagent may be compared with a delayed-action bomb.

PHYSICAL METHODS OF WATER DECONTAMINATION

Among the diversity of the existing methods of water decontamination, reagent-free methods are most promising from the viewpoint of technological, economic, hygienic and ecological features. Among these methods, the ideas of non-traditional use of physical effects and phenomena find an increasing application.

In this respect, hydrodynamic cavitation is interesting. This is the only kind of cavitation allowing the treatment of a large volume of water with minimal material expenses. Its efficiency is not affected by water turbidity, salt composition, pH. In addition, cavitation destroys colloids, suspension particles on which and inside which bacterial exist, thus destroying their protection from chemical and physical bactericidal agents.

For instance, drinking water decontamination with **ultrasound** is based on its ability to cause cavitation – the formation of cavities creating a large pressure difference, which causes the rupture of cell shells and the death of bacterial cells. The bactericidal action of ultrasound at different frequencies is substantial and depends on the intensity of sound vibrations.

Among the physical methods of drinking water decontamination, **disinfection with UV rays** is widespread. The bactericidal action of these rays is due to their effect on cell metabolism and especially on the enzymatic systems of a bacterial cell. Ultraviolet rays destroy not only vegetative bacterial forms but also spores, and do not change the organoleptic properties of water [17]. It is important to stress the absence of the upper threshold of the dose because no toxic products are formed during irradiation with UV rays. The desirable level of decontamination may be achieved almost in all cases by an increase in the dose of UV radiation.

The main disadvantage of this method is a complete absence of aftereffect and insufficient power of lamps for a large volume of water. The unit of UV decontamination is located at the stage of final water treatment before supplying it into the network. UV installations are most attractive for individual water supply. Preliminary results have been obtained, demonstrating the potential of the replacement of traditional high-pressure UV lamps by the UV light-emitting diodes [10]. The authors used UV light-emitting diodes with peaks at 267, 275, 310 nm and combined radiation at 267/275, 267/310 and 275/310 nm for the system of the periodic disinfection of water. An ultraviolet light-emitting diode with the wavelength of 267 nm demonstrated the highest efficiency of the inactivation of the model *E. coli* bacteria. However, the studies are not completed yet, and it is yet difficult to make any conclusions.

During recent years, water decontamination with the help of **gamma radiation** is developing. This method possesses all advantages of reagent-free methods. No foreign substances are added into the water during the treatment with gamma rays. The natural chemical and organic properties of water are not changed. With the appropriate dose rate, microorganisms die very quickly; water may be supplied to consumers immediately after irradiation. Gamma radiation has one more advantage in comparison with the UV radiation. Gamma rays are absorbed by water with lower intensity, which is important for the treatment of large amounts of water.

The sources of gamma radiation in the installations for water disinfection may be fuel elements worked out in nuclear reactors. Water disinfection in these gamma installations is considered to be economically profitable. Experimental studies in the USSR involved radioactive cobalt with the half-decay period equal to 5.3 years. Long-term operation of the source of gamma radiation provides minimal expenses for service and maintenance of the installations for water disinfection. The major part of bacterial (90 %) die at relatively low radiation doses; the higher is the dose rate of gamma rays, the lower dose is necessary for 100 % disinfection of water. With respect to a decrease in radio-resistance, the intestinal and typhoid group of bacteria are arranged in the sequence: paratyphoid B agent, typhoid, and dysentery. The doses of gamma rays causing complete inactivation of pathogenic microorganisms were lower than in the case of *E. coli* in the same concentration. This is confirmed by the sanitary indicator value of *E. coli* for the control of water disinfection with gamma radiation. So, water disinfection with gamma radiation got a principally positive hygienic mark but the application of this method has not developed yet.

Among the physical methods of water decontamination, one of the most widespread and reliable methods is **boiling**. In addition to the destruction of bacteria, viruses, bacteriophages, antibiotics and other biological objects that are often present in open water sources, gases dissolved in water are removed, and water hardness decreases. The taste of water changes only slightly as a result of boiling.

COMBINED METHODS OF WATER DISINFECTION

At present, a principally new direction of water treatment at water supply facilities is under development at A. V. Dumansky Institute of Colloid Chemistry and Water Chemistry, NAS of Ukraine. This direction is illustrated schematically in Fig. 1.

At the first stage of the treatment of surface water, as the source of drinking water supply, it is blown with air using ceramic membranes. Thus insoluble admixtures are removed by floatation. Then water in the accumulating tank is treated with a coagulant (aluminium sulphates or hydroxochlorides) and filtered through a column with quartz sand to prevent pipeline biofouling and to enhance the efficiency of disinfection of purified transparent water after filtering. Then transparent water is treated with UV radiation (this process is most efficient in transparent water). Decontaminated water in a closed reservoir is treated with carbon dioxide from a gas cylinder through a membrane to generate CO_2 microbubbles for conservation, then water is kept for a definite time, and again saturated carbon dioxide to pH 5.5–6.5. At pH within this range, carbon dioxide is present in water in the form of free gaseous CO_2, which does not exhibit corrosiveness against the pipelines. Thus conserved water is characterized by the long-term aftereffect of disinfection with UV radiation, which was confirmed by microbiological studies. Suppression of the growth and reproduction of microflora in the distributing network is observed. In addition, resulting water does not have odour and unpleasant taste, and these parameters are unchanged for several days. Consumers may use tap water for drinking and for cooking after additional disinfection by boiling. This water does not contain carcinogenic substances formed during chlorination. Water acidified with carbon dioxide will prevent biofouling of pipelines, and residual CO_2 will be evaporated during boiling.

The conserving effect of CO_2 was tested additionally in sparkling waters after the introduction of microscopic *Aspergillus niger* fungi isolated by us from water supplied to the institute, and identified in the Institute of Urology of the Academy of Medical Sciences of Ukraine (Table 1).

Thus, carbon dioxide may be used to decontaminate water purified at the station of water preparation because this gas is efficient in suppressing the development of various microflora.

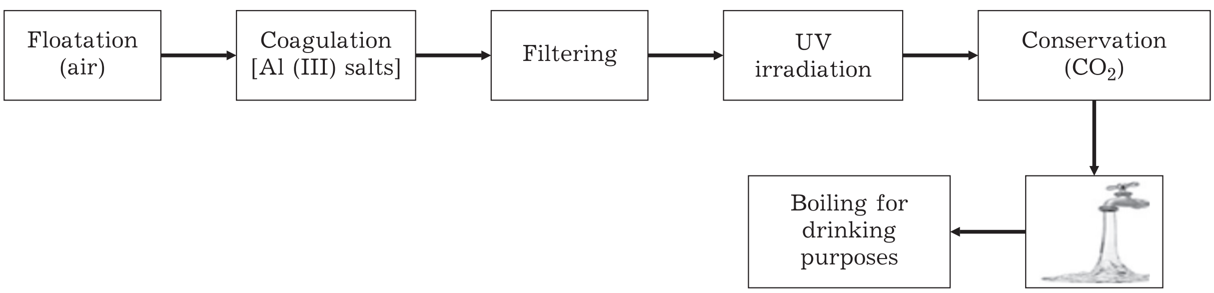

Fig. 1. Schematic diagram of water treatment at the stations of centralized water supply.

TABLE 1

Evaluation of the effect of different degrees of gas saturation of bottled water on the viability of *A. niger*, CFU/cm^3

Duration of observation, min	Water	
	Strongly aerated water	Weakly aerated water
0	$7.0 \cdot 10^2$	$6.0 \cdot 10^2$
30	$1.7 \cdot 10^3$	$1.2 \cdot 10^3$
60	$8.0 \cdot 10^2$	$7.5 \cdot 10^2$
120	$8.2 \cdot 10^2$	$1.0 \cdot 10^3$
1440 (24 h)	$6.0 \cdot 10^2$	$9.0 \cdot 10^2$
4320 (72 h)	$1.1 \cdot 10^2$	$1.0 \cdot 10^2$

The decontaminating action of carbon dioxide may be substantiated by the below-described mechanisms relying on the experimental data and the information reported in publications [18]:

a) change of pH of water medium. The majority of substances dissolve in water, in particular carbon dioxide. CO_2 molecule is non-polar, however, it able to interact with water due to unshared electron pairs of each oxygen atom. The electron density may be partially transferred to the positively charged hydrogen atoms of water molecule similar to the formation of hydrogen bonds between water molecules themselves. However, the dissolution of CO_2 in water involves the establishment of the equilibrium with the participation of carbonic acid (H_2CO_3) and the ions, HCO_3^- and CO_3^{2-}. The ions orientate water dipoles forming the hydrate shell, similar to any other ion dissolved in water. The indicated reaction is characterized by slow kinetics. In the equilibrium state, only 0.2–1 % of dissolved CO_2 is transformed into H_2CO_3. The major part of CO_2 remains in the form of gas molecules surrounded by water molecules (hydrated gas). Carbonic acid is a weak acid, it dissociates stepwise with the formation of HCO_3^- and then CO_3^{2-}, with the release of H^+ ions. The latter ions cause a decrease in pH of water, which has a negative effect on bacterial cells and prevents the growth of microbes. Water acidification causes a decrease in the resistance of microorganisms due to higher energy consumption for the maintenance of the optimal pH of homeostasis;

b) damage to the membranes. Cell membranes of bacteria preventing the cells from hazardous action of the environment are composed mainly of lipopolysaccharides and phospholipids and are stabilized due to the presence of Ca^{2+} and Mg^{2+} ions. Only the substances possessing high diffusion capacity may penetrate through this membrane. Carbon dioxide is the substance of this type. It readily penetrates through a double phospholipid layer. When the ionized CO_2 molecule gets into the membrane, its lipid phase gets disordered, and the structure becomes distorted. The size of CO_2 molecules is 3.4 E, which is much smaller than the size of phospholipids (20–50 E), so they readily penetrate through the cell membrane and damage cell cytoplasm;

c) a decrease in pH of the intracellular medium. After penetration inside the cell, CO_2 molecules accumulate and decrease intracellular pH. A bacterium may survive in the acid medium only if its internal medium remains neutral. To compensate for acidity level, the cells use the buffer capacity of the cytoplasm, the system of proton "pumping", and the mechanisms of the production of acids and bases. When CO_2 concentration inside the bacterial cell approaches saturation and the excessive amount of H^+ ions is formed, the homeostatic system of the organism changes, the release of protons outside becomes hindered, the buffer capacity of the cytoplasm is exhausted, and the cells stop to produce bases that would neutralize the excessive hydrogen ions. Because of this, a decrease in pH of the intracellular medium is the major factor in the mechanism of microorganism inactivation by treating water with carbon dioxide.

Investigation of the mechanisms of the disinfecting action of carbon dioxide is relevant and requires further refinement and development.

So, the proposed new approach to the technology of centralized water preparation at water stations is a promising direction of the treatment of drinking water and may be used instead of chlorination.

CONCLUSION

Disinfecting agents based on chlorine are most frequently used to decontaminate water due to the cheapness and simplicity of application. However, the indicated disinfectants possess a number of substantial disadvantages.

Any treatment of drinking water with chlorine, which is very dangerous in the application, or with its derivatives is unsuitable because these products were obtained artificially and bring hazards to humans and to the environment.

For several million years, people had been drinking natural high-quality water free from chloroorganic compounds or other dangerous substances. With the start of the industrial revolution at the end of the XIX century and the beginning of the XX century, the situation had changed. All-round water chlorination was introduced, which played initially a positive role against epidemics of widespread diseases, but then grew into a threat to human health due to the formation of a very large number of very toxic side products of disinfection.

It is demonstrated that the new approach to the technology of centralized water preparation at water stations by means of decontamination of purified transparent water with UV radiation after its treatment by means of coagulation and filtering, followed by saturation with carbon dioxide for conservation, is a promising direction in the technology of drinking water preparation and may be recommended instead of chlorination, which has become a real scourge of the XX century.

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