Journal of Russian Laser Research, Volume 26, Number 1, 2005

NEW PHYSICAL METHODS OF DISINFECTION OF WATER

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Abstract

A short analysis of the contemporary techniques of water disinfection as well as of the effects arising from the magnetic treatment of water is carried out. The experimental results of water disinfection in constant magnetic and electric fields are presented. The maximum disinfection efficiency exceeds 99%. A theoretical model is developed that describes the effects arising in water after its treatment by constant magnetic and electric fields on the basis of "free" dipoles. The anomalous properties of water are shown to be retained more than two hours after its treatment. It is rather important that the expenditure of energy in the techniques considered is virtually nil.

Keywords: disinfection, magnetic field, electric field, water, microorganisms, dipole.

1. Introduction

Environmental protection is a central problem challenging mankind in the present century. In this context, water being the foundation of life on Earth, deserves particular attention. Efficient recycling of purified and treated sewage for various needs of the national economy contributes significantly to water conservation.

The disinfection of water is of prime importance both for the animal world and humans, since the purity of water including the presence of pathogens affects the health and life span. The presence of microorganisms in water may cause a great many diseases including the hepatitis, cholera, typhoid fever, dysentery, and others. To avoid this, one has either to prevent the microorganisms from reproduction or to kill them.

Chemical, i.e., reagent, techniques based on the use of a broad range of chemical agents are commonly used to disinfect water. Among them are chlorine and chlorine-containing compounds (chlorine gas, chlorinated lime, sodium hypocloride, and active chlorine, produced in special electrolyzers made of table salt, chloramines, and others) as well as ozone, fluorine, iodine, ions of heavy metals (including silver), and a number of other substances.

Chlorination has gained the most acceptance among the reagent techniques to date. The main reasons for this are the high reliability of the bactericidal effects, the possibility of rather simple monitoring of the residual chlorine, the simplicity of the corresponding equipment, and others. However, in the case where

Translated from a manuscript submitted June 11, 2004.
1071-2836/05/2601-0013 ©2005 Springer Science+Business Media, Inc.

some organic substances remain in water, chlorine reacts with them forming carcinogenic substances. Among the latter are chloramines that induce the cancer. Because of this, drinking water should be carefully purified from organic compounds prior to chlorination.

A similar drawback is also inherent in disinfection processes based on ozone treatment. So-called ozonides are formed on interaction of ozone with some organic compounds. These ozonides also belong to the category of carcinogenic substances.

Moreover, many reagents are toxic and necessitate safety precautions in their transit and dosage. Some of them when applied result in variations in the composition and properties of water and adversely affect animal and plant life. For this reason, reagent techniques cannot fully meet modern requirements on the disinfection of water.

The reagentless techniques are of great interest. These physical methods are based on the use of various physical fields for disinfection. Among them are ultraviolet rays, electric discharges in water, cavitation, ultrasound, and so on. An important advantage of physical techniques is their ability to act directly on microorganisms, leaving the properties and composition of water virtually intact. Ultraviolet disinfection is the most economical technique. Mercury-vapor lamps possess a high efficiency (30–40%) of conversion of electric energy to radiation with a wavelength of about 254 nm. The absorption band of nucleic acids (the foundation of life) peaks at 260 nm. Because of this, the doses needed to kill the microorganisms are insignificant. They are different for each type of bacteria but mainly fall within the range of 6–100 mJ/cm^2. However, radiation should hit the microorganism directly. In the case where the water contains suspension particles, they can shield the bacteria from radiation and reduce the disinfection efficiency. Moreover, many microorganisms attach to the surface of suspension particles or penetrate into their pores. Thus, to provide efficient disinfection of water by ultraviolet radiation, one has to remove both the particles suspended in it down to a concentration below 3 mg/liter and the organic compounds that absorb radiation with a wavelength of about 254 nm.

As for other physical methods, they are only under development and generally require large consumption of energy.

In this paper, we present the results of experimental studies and theoretical analysis of the disinfection process of aqueous media by means of magnetic and electrostatic fields.

2. Effects Observed with Magnetization of Water Systems

A wealth of material on the action of magnetic fields on water systems is collected in [1]. The physical and chemical properties of both water and the impurities in it change during the magnetic treatment of water in the cases where either the field is changed (pulsations of the constant field) or the liquid flows, crossing the magnetic field. The effect is minimum with a constant or pulsating magnetic field in the absence of flow with respect to the field.

The magnetic treatment of water results in many unexpected effects:

- The surface tension and electrical conduction of water increase with its motion in a geomagnetic field [1, 2]. However, the presence of surface-active substances in certain concentrations in water results in an adverse effect: the surface tension decreases.
- The solution rate of oxygen increases.
- Hydrogen peroxide in small concentrations ($5 \cdot 10^{-5}$–$1.7 \cdot 10^{-4}$%) is formed.

- The catalytic processes of oxidation of the organic substances (e.g., of oxalic acid) speed up.
- The chemical activity of the oxygen dissolved in water increases. This results in the variation in wetting power and biological activity of water.
- The microbial growth speeds up significantly (by a factor of 1.5–1.7) [1,3].
- The Coli-index $N_{E.C.}$ (*E. Coli*) of water of the Severnyi Donets River and Kharkov plumbing decreases by 81–97% [4].

Moreover, the magnetic treatment of water was found to increase the permeability of biological membranes of frog cells [1]. A lot of other effects observed on magnetic treatment of water can be presented [1].

However, the processes caused by the magnetic treatment of water are not completely understood up to the present. It is especially significant that modern notions of its action on various objects are usually based on the energy contributed to the object. From this standpoint one can neglect the energy contributed to water passed through a magnetic field even with a large magnetic induction ($\sim$1 T). However, this consideration does not take into account the fact that the polarization of water occurs due to the action of the Lorentz force on charged particles, including dipoles. This changes significantly the properties of water and of the dissolved impurities and strongly affects the vital functions of microorganisms present in the water.

Besides the action of the Lorentz force the magnetic field can also change significantly the ratio of water molecules in the ortho- and para states.

Note that polarization of water also takes place in an electric field. In this case, the effect can be observed both in the flow crossing the electric field and (as distinct from the magnetic field) in the water at rest.

Some aspects of the remarks presented will be discussed below.

3. Experimental Studies

The results of preliminary experimental studies of the action of longitudinal and transverse magnetic fields on biological objects contained in a water flow which crosses magnetic fields are presented in [5]. A number of effects were found, including an increase in the vital functions of microorganisms in flow in a longitudinal magnetic field. To the contrary, a bactericidal effect occurs in flow in a transverse magnetic field. The magnetic inductions were nearly the same in both cases. However, the disinfection effect in a transverse magnetic field was 98.8% for coliphages, 92% for general coliform bacteria, 94% for gram-negative microflora, and 80.6% for thermotolerant coliform bacteria.

In the present section we discuss our further experiments on water disinfection in magnetic and electrostatic fields in the case of flow rates ≥ 1 m/s.

Experimental studies were performed on a set-up which included an acrylic-plastic tank with a volume of 10 liters filled with water containing microorganisms. The latter included *E. Coli* ones. The pipelines were made from polyethylene and rubber. The set-up also included a water pump with a flow rate up to 10 liters/s and a ball cock at the outlet. Plane magnets ($25\times25\times10$ mm) provided magnetic induction between them up to 0.2 T. Two metal plates (of size $25\times25\times1$ mm) formed a plane capacitor. The

TABLE 1.

Number of pairs of magnets	0	1	1	2	1	2	1	2
v, m/s	-	1.04	1.04	1.04	1.04	6.5	1.04	1.6
$N_{E.C.}$, liter^{-1}	7000	3000	3600		1600		3200	
$\eta, \%$	-	57	49		77		54	

magnets and the capacitor were situated outside the pipelines. In addition, Petri dishes with plates of the plane capacitor at the top and bottom were used. The plates fully covered the dish surface.

The water discharge was controlled by pipes with different inner diameters placed at the outlet of the pump (i.e., by variation in the water flow resistance at the pump outlet). The magnets and the capacitor were placed at different sections of the pipeline, i.e., in the regions with different flow rates (from 0.5 to 6 m/s). Water sampling for measurements of the Coli-index $N_{E.C.}$ was performed at the outlet of the pipeline from the pump. The Coli-index was measured by the conventional technique.

First and foremost, it should be noted that in various experiments performed in different seasons the degree of disinfection of water in transverse magnetic and electrostatic fields varied within wide limits and reached a maximum value above 99%. The degree of disinfection of water was affected by the following parameters:

- the initial content of the microorganisms $N_{E.C.}$;
- the flow rate and flow behavior at the location of the magnets or the capacitor;
- the water conductivity (i.e., the salt content);
- the number of pairs of magnets at the pump outlet and their location at pipelines of different diameters;
- the strength of the electrostatic field in water.

Let us describe the results of the most typical experiments. In the experiment performed on August 20, 1998 the flow rate was 0.97 m/s. Up to three pairs of magnets spaced at 200 mm were used. The initial contamination was characterized by $N_{E.C.} = 3.4 \cdot 10^6$ liter^{-1}. With the first pair of magnets the disinfection was $\eta_1 = 29.4\%$. With installation of two pairs of magnets the disinfection was $\eta_2 = 32.4\%$. Three pairs of magnets resulted in a disinfection of $\eta_3 = 69.1\%$.

In the experiment performed on April 12, 2000 one and two pairs of magnets were used. The second pair of magnets was positioned at different points of the pipeline at an increasing distance from the first pair. In this case, the flow rates differed from those at the location of the first pair of magnets. The results are represented in Table 1. Note that the second pair of magnets was placed parallel to the first one but the relative orientation of the induction vector $\vec{B}$ in these two pairs of magnets was not controlled.

The second set of experiments was carried out according to a scheme differing from those previously described. Water traveling through three or two pairs of magnets was returned to the tank in the form of a jet inclined with respect to the water surface in it. In this case, aeration of the jet occurs. After

TABLE 2.

Date	09.28.1999		10.26.1999		11.01.1999	
v, m/s	1.53		0.78		0.78	
Number of pairs of magnets	3		2		2	
	$N_{E.C.}$, liter^{-1}	$\eta, \%$	$N_{E.C.}$, liter^{-1}	$\eta, \%$	$N_{E.C.}$, liter^{-1}	$\eta, \%$
Initial	16000	-	2000	-	20000	-
$m = 1$	5000	68.8	1000	50	2000	90
$m = 2$	5000	68.8	1000	50	1600	92
$m = 3$	15000*	-	0	> 50**	400	98
$m = 4$	4000	73.3	0	> 50**	0	> 99.5**
$m = 5$	800	94.7	0	> 50**	0	> 99.5**

* The pollution presumably occurred here. Thereafter the calculation was carried out with respect to $N_{E.C.} = 15000$ liter^{-1}.

** The true value is greater than that presented. The latter was calculated with consideration for the quantity sampled for analysis.

TABLE 3.

Date	10.04.1999		10.08.1999		
	$N_{E.C.}$, liter^{-1}	$\eta, \%$		$N_{E.C.}$, liter^{-1}	$\eta, \%$
Initial	4000	-	Initial	11300	-
Magnets	200	95	Magnets	1200	89
Magnets + 1.5 g/liter	900	77.5	Magnets + 0.65 g/liter	3800	66

measuring the initial contamination $N_{E.C.}$ the measurements were repeated at intervals necessary to pass the whole volume of water in the tank through the magnets m times, where $m = 1$–5. The results are presented in Table 2.

In the further experiments the salt NaCl was added to the infected water with an initial conductivity equivalent to a NaCl content below 0.05 g/liter. The results are indicated in Table 3. A single pair of magnets was used in the experiment, and the flow rate was 0.98 m/s.

In the case of flow in a transverse magnetic field the ions contained in water were shown to move rectilinearly in the direction perpendicular to that of the velocity of water [5]. Thus, the motion of ions is similar to their motion in the electric field. Relying on these experiments, we assumed that the action of the constant electric field on the infected water should also be accompanied by the disinfection effect. The first experiments confirmed this conclusion.

TABLE 4.

U, V	0	10	20	30	41
$N_{E.C.}$, liter^{-1}	6500	1060	600	260	60
η, %	-	84	91	96	99
B_{eq}, T	-	7.6	15.2	22.9	31.3

TABLE 5.

	η (general microbe number), %	η (E.C.), %	η (thermotolerant), %
NaCl (0.5 g/liter)	60	57	above 90
NaCl (2.0 g/liter)	0	0	67

In the experiment on October 25, 1999 the two pairs of magnets were replaced by a couple of duralumin plates with dimensions of 25×25 mm. A dc voltage of 30 V was applied to these plates. The flow rate was 0.9 m/s and the distance between the plates was 20 mm. The disinfection effect was $\eta = 90\%$ with the initial $N_{E.C.} = 1000$ liter^{-1}.

This experiment was repeated on November 02, 1999. Its difference from the previous experiment lies in the fact that the flow rate was $v = 0.82$ m/s and $N_{E.C.}$ was measured more carefully (large volumes of water were taken for the analysis). The results can be found in Table 4. Here, U is the voltage across the plates, B_{eq} is determined from the equality of the Lorentz force and the force of the electric field exerting on the charge, $B_{\text{eq}} = E/v$, and $E = U/\varepsilon d$. Thus, with the known permittivity of water $\varepsilon = 80$ we have $B_{\text{eq}} = 0.76U$ T.

The action of the electric field should manifest itself both on the moving and the stationary water as distinct from the experiments with magnetic fields. Because of this, further experiments were carried out with water at rest using Petri dishes.

The experiments were first performed with a duration of action of the constant electric field of 5 and 10 min. With an alternating field with frequency $f = 50$ Hz ($U = 220$ V, $d = 21$ mm), disinfection effect was absent.

The experimental results show that the disinfection effect occurs with the action of the constant electric field on the water at rest. In this case, actions with small durations (from 3 s to 10 min) reveal the magnitude of the disinfection effect.

The experiments performed in late December, 2000 on Petri dishes with $U = 220$ V and $d = 22.5$ mm showed that η was within the range of 74–90% for *E. Coli* and about 50% for for the general microbe number. Unfortunately, the water temperature was not measured in this set of experiments.

On January 30, 2003 the influence of the water conductivity on the disinfection effect was studied as before. The distilled water was infected and the salt NaCl was added. The experiment was performed in Petri dishes on treatment with the electric field ($U = 220$ V and $d = 22.5$ mm). The results are tabulated in Table 5.

The aftereffect of water treated with an electric field on the disinfection of microorganisms was then studied. The following experiment was performed on June 03, 2003. The Petri dishes were filled with distilled water at $T \approx 15°$C and treated with the field at $U = 220$ V during 2 s. Two hours later the contaminants were added. The disinfection effect was 89%.

A similar experiment was carried out on July 09, 2003. The only differences from the previous one were the water temperature $T = 28°$C and the larger volumes of water sampled for analysis. The disinfection effect was characterized by $\eta_{E.C.} = 60\%$ ($\tau = 0$), $\eta_{E.C.} = 40\%$ ($\tau = 30$ min), and $\eta_{E.C.} = 20\%$ ($\tau = 90$ min), where τ is the time of contamination of the water after its treatment with the field.

4. Analysis of the Results Obtained

The main result of the studies discussed consists in the fact that the treatment of water with constant transverse magnetic and electric fields always gives rise to the disinfection effect. The magnitude of this effect depends on the experimental conditions and can exceed 99.5%. Treatment with an alternating electric field ($f = 50$ Hz) does not affect the degree of water contamination.

Another important result lies in the fact that the magnitude of the bactericidal effect depends on the conductivity and temperature of water. Moreover, the water preserves its bactericidal properties for several hours after the electric treatment. To date, this facts remain unexplained.

Let us describe the causes for the effects observed. First we consider the process of magnetic treatment of water. As was already discussed in Sec. 2, charged particles in the flow crossing the magnetic field are subjected to Lorentz force. Moreover, transitions between the ortho- and para states of water molecules are possible in a magnetic field. Thus, the relative content of these molecules can be altered.

The results of the magnetic treatment of water in longitudinal and transverse magnetic fields are discussed in Sec. 3. The longitudinal field was created with a solenoid. The magnetic field $\vec{B}$ inside the solenoid is directed parallel to the velocity of the water flow. However, close to its ends the magnetic field lines spread out (converge) like a fan, forming small angles α with the velocity of the water flow $\vec{v}$. Because of this, the Lorentz force acts on the charged particles in the flow regions close to the solenoid ends. Under the action of this force the ions were shown [5] to move rectilinearly and perpendicular to $\vec{v}$ with rather small velocities ($v_{\rm ion} < 0.01$ μm/s). The Lorentz force is given by the expression

$$\vec{F}_L = q[\vec{v}\vec{B}], \quad F_L = qvB\sin\alpha, \tag{1}$$

where q is the charge of the particle.

Taking into account that $v \approx$ const (because of the small $v_{\rm ion}$), it follows from (1) for the constant α that the ions in the water flow move similarly to their motion in the electric field when considered in the coordinate system linked with this flow. We have

$$\vec{F}_{\rm el} = q\vec{E}. \tag{2}$$

Here, $\vec{E}$ is the field strength in water. In this case, the equivalent field strength $E_{\rm eq}$ acting with the force $F_{\rm el} = F_L$ is defined by the expression

$$E_{\rm eq} = vB\sin\alpha. \tag{3}$$

From the above discussion it follows that in a water flow crossing a magnetic field $\vec{B}$, polarization of the water should be observed similarly to that in an electric field. This polarization is associated with the action of the electric field on the dipoles of H_2O molecules.

Inside the solenoid $\alpha = 0$ and there is no action on the dipoles of water molecules. Near the solenoid ends α is small but nonzero. Thus, polarization of water should be observed. In this case, the polarization has circular behavior. When the polarization direction at the input of the solenoid is, e.g., clockwise, it should be counterclockwise at the output of the solenoid. In a transverse magnetic field, linear polarization takes place. Therein lies a fundamental difference between the action of magnetic treatment on water and the microorganisms in it in longitudinal and transverse magnetic fields.

In a transverse magnetic field between two magnets both at the input into the space between them and at the output, the polarization direction is opposite to that between the two magnets. However, the magnetic induction $\vec{B}$ between the magnets significantly exceeds that at the input and output. Thus, in the case of the magnetic treatment of water with the solenoid, water is circularly polarized at its input and virtually depolarized at the output. That is to say, the main effect of action on the microorganisms can be a change in the ratio of water molecules in the ortho- and para states. This ratio at rest is 3 : 1.

Thus, the main effect resulting in the increase in the vital functions of microorganisms is presumably associated with variation in the ratio of water molecules in the ortho- and para states. From all appearances the linearly polarized water possesses a bactericidal effect. In this case, the fulfillment of two conditions, $\alpha > 0$ and $\alpha = \text{const}$ in the gap between the magnets and in the region of the constant magnetic field, is of prime importance. From the aforesaid, it might be assumed that water treated with a constant electric field also possesses bactericidal properties.

An increase in the water conductivity results in a decrease of the disinfection effect. This is due to the fact that upon magnetic and electric treatment of water, free charges are formed at the phase boundary (e.g., solid–liquid, gas–liquid, liquid–liquid with different conductivities) because of the action of the Lorentz force and electric field on the ions contained in water. These free charges create an electric field $\vec{E}_{\text{scr}}$, which is in opposition to $[\vec{v}\vec{B}]$ and $\vec{E}$. Thus, both the Lorentz force and the electric field acting on the charges are screened.

Let us now discuss the relation between the polarization of water and the bactericidal effect produced by the magnetic and electric treatments of water. The following fact should be primarily pointed out. When the electric field E_0 acts on water, the field strength decreases by a factor of ε (where, as above, ε is the relative permittivity of water, which value is due to the water dipoles). In this case, the force acting on the charges in water is expressed as

$$\vec{F}_{\text{el}} = \frac{q}{\varepsilon}\vec{E}_0 = q\vec{E}, \tag{4}$$

where $\vec{E}$ is the electric field strength in water.

As indicated above, the magnetic field $\vec{B}$ acts on the charges in water that move with its flux with respect to $\vec{B}$ in the same way as the electric field $\vec{E}$. The only difference is the direction of these forces [see (1) and (2)]. Because of the polarization of water, the Lorentz force should also decrease by a factor of ε. Thus, formula (1) for the Lorentz force, which defines the action on the charges in the water flux crossing the magnetic field $\vec{B}$, should be written in the form

$$\vec{F}_L = \frac{q}{\varepsilon}[\vec{v}\vec{B}]. \tag{5}$$

We now discuss the effect of polarization on microorganisms. Both short-range and long-range orders are known to take place in water under some conditions. The conservation of the new structural state of water under magnetic treatment is discussed in [6]. This state is explained by the change in the relationship between the ortho- and para states of water. However, in a series of papers (see, e.g., [7]) such an explanation was shown to be improbable. The geometrical model of the stable structural formation of water molecules was constructed on the basis of these papers. All H_2O dipoles in this formation are "closed" between each other in such a way that the strength of the electrostatic field at the surface of this structural unit is virtually zero. Each such unit consists of 57 water molecules. A new form of intermolecular interaction [8] arises between these units. This can add complexity to the structure of water.

The fact that virtually all dipoles are "closed" between each other in the steady state of water is rather important for us. As mentioned above, the action of the external electric field on water results in its polarization (the orientation polarization). According to the above discussion, a similar situation occurs in the water flux crossing the magnetic field. The polarization gives rise to the water's own macroscopic electric field [9] produced by the dipoles of H_2O molecules. In this way, "free" dipoles are formed in water that is "closed" without the field. Bound or polarization charges arise at the water surface (at the boundary between the two phases). These charges produce an electric field $\vec{E}_p$ in opposition to the external field $\vec{E}_0$ [9].

It makes no difference whether the free "dipoles" arise in the structural units of water or in separate molecules. An important point is that the electric field arises close to them, which can affect the properties of water and everything in it, including the microorganisms.

Biological membranes are among the key units that provide structural isolation and integrity of cells [10]. The molecular model of the cell membrane formed by the lipid bilayer (associated with surface-active proteins) was proposed by Dannely and Devson in 1935. The lipid bilayer is formed by two lipid layers with the polar heads on the outside and inside of the bilayer. The thickness of the lipid bilayer is 5–7 nm, the distance between the molecules is 0.46–0.47 nm, and the area that falls on one phospholipid molecule is 0.48 nm^2 at 25°C [10]. Thus, the polar heads, i.e., the dipoles, are situated on the outside of the bilayer facing the water. Therefore, the strength of the electrostatic field close to the microorganism surface should be evaluated.

For this purpose, let us consider two planes formed by unlike dipole charges with a plane separation l determined from the equality $\vec{p}_e = q\vec{l}$. In this case, the dipole moment $\vec{p}_e$ is perpendicular to the plane, q is the dipole charge (positive or negative), and l is equal to the distance between the dipole charges. Let us denote the plane dimension by R (the plane radius), the distance from the nearest plane to the measurement point E by r_0, and the surface charge density by σ. Then we have $dE = \sigma ds/(4\pi r_0^2 \varepsilon_0 \varepsilon)$. After integration of this equation over s and substraction of the field strength of the second plane from that produced by the first one (closest to the measurement point at the distance r_0), we obtain

$$E = \frac{\sigma}{2\varepsilon_0\varepsilon}\left[\frac{r_0 + l}{\sqrt{R^2 + (r_0 + l)^2}} - \frac{r_0}{\sqrt{R^2 + r_0^2}}\right]. \tag{6}$$

From (6) it follows that $E \to 0$ with $l \to 0$. Thus the value of E decreases when the dipole moments form some angle $\alpha > 0$ with the perpendicular to the plane and $\alpha \to 0$. With $\alpha = 90°$ (the dipole moments are parallel to the plane) we have $E = 0$. With $R \gg (r_0 + l)$ expression (6) takes the form

$$E = \frac{\sigma}{2\varepsilon_0\varepsilon} \cdot \frac{l}{R}\,. \tag{7}$$

We evaluate the field E produced by the microorganism surface facing the water (the environment). For this purpose we take $R = 10^{-6}$ m, $l = 0.3 \cdot 10^{-10}$ m, $\varepsilon = 80$, $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m, and $\sigma = 0.33$ C/m^2.

For these values of parameters expression (7) is accurate to a good approximation. In this case, we have $E = 7 \cdot 10^3$ V/m. This is the field strength produced above the outer surface of the bilayer. The inner surface produces the reverse field. To evaluate the true electric field strength above the surface of the lipid bilayer, one should take into account also its inner surface. We use exact expression (6) for this purpose. Taking $r_0 = 3 \cdot 10^{-10}$ m and the thickness of the lipid bilayer as $5 \cdot 10^{-9}$ m, we obtain $E_{\text{true}} = 0.3$ V/m. Thus, the electric field strength in the vicinity of the microorganism surface in water is close to zero even in the case where the dipole moments of the polar heads of the lipids are perpendicular to the cell surface. According to (6), the field strength decreases as the distance from the cell surface increases.

In the electric field with the nonzero gradient the dipoles are subjected to the force

$$\vec{F}_g = \text{grad}(\vec{p}_e \vec{E}) = p_e \frac{d\vec{E}}{dr_0}\,. \tag{8}$$

The force $\vec{F}$ is directed along the vector $d\vec{E}/dr_0$, i.e., to the domain of high $\vec{E}$. Thus, the dipoles are attracted to the bilayer. This is possibly due to the fact that the surface of the majority of living cells is hydrophilic (the wetting angle is below 90°). However, this force is small, and in the case where a free dipole is at the surface of the structural unit of water, its velocity of motion towards the microorganism is negligible.

This is the situation in the vicinity of the microorganism in water.

We now consider the "free" dipole of the water molecule and calculate the field strength close to it. The module of the electric field strength at the distance r from the dipole has the form [9]

$$E = \frac{p_e}{4\pi\varepsilon_0\varepsilon r^3}\sqrt{1 + 3\cos^2\Theta}. \tag{9}$$

Here, Θ is the angle between the vector of the dipole moment and the direction toward the measurement point, which is at a distance r from the dipole center. The value of E takes its minimum at $\Theta = 90°$, i.e., the measurement point is on the straight line passing between the dipole charges and perpendicular to $\vec{p}_e$.

For the water molecule we have $p_e = 6.17 \cdot 10^{-30}$ C/m. Setting then $r_1 = 3 \cdot 10^{-10}$ m and $r_2 = 5.3 \cdot 10^{-9}$ m (the membrane thickness is ≈ 50 Å), we obtain at the points 1 and 2 $E_1 = 2.6 \cdot 10^7$ V/m and $E_2 = 4.7 \cdot 10^3$ V/cm, respectively. This is the field strength in water at the membrane surface E_1 when the dipole is situated parallel to it at a distance of 3 Å and at the backwall of the binary bilayer provided that the membrane permittivity is the same as ε for water.

It is well known that the membranes of microorganisms contain pores. According to [10], the pores formed as a result of the external electric field applied to the microorganism start to grow unrestrictedly after attainment of some critical size. This causes the breakdown of the membrane and the microorganism's death. The values of E_1 and E_2 are presumably sufficient for such a process.

Thus, the formation of "free" dipoles in a water flux in the electric field when the flux crosses the magnetic field may result in the death of the microorganism, i.e, in the disinfection of water.

As discussed above, the "free" dipoles are formed in particular at the phase boundary. They can also be formed at the surface of the microorganism. We evaluate their number when a potential of 100 V is applied to the water and the plate spacing is $d = 1$ cm.

The field strength in vacuum E_0 is attenuated by a factor of ε because of the polarization of water. In other words, the field E_p is formed in water because of the bound or polarization charges at its surface. This field is opposite in direction to the field E_0 and equals $E_p = (\varepsilon - 1)E_0/\varepsilon$.

The amount of polarization charges (of dipoles at the water surface) in the plane capacitor is $q = CU = \varepsilon_0 \varepsilon S E_p$. In the case under consideration the number of dipoles is $q = 4.4 \cdot 10^9$ cm^{-2} when the area $S = 10^{-4}$ m^2. Thus, the mean distance between the dipoles is $\bar{r} = 1/\sqrt{q} = 0.15$ μm. From this it follows that the mean number of dipoles in 1 cm^3 is $N = q^{3/2} = 2.9 \cdot 10^{14}$ cm^{-3} $= 2.9 \cdot 10^{17}$ liter^{-1}. This value was obtained with a rather high field strength $E_0 = 10^4$ V/m.

As mentioned above, in the case of water motion in a transverse magnetic field the electric field E_p arises due to formation of "free" dipoles. The magnitude of this field opposing the Lorentz force is equal to $\vec{E}_p = -[\vec{v}\vec{B}](\varepsilon - 1)/\varepsilon$.

Under the experimental conditions discussed in Sec. 3 we have $B = 0.2$ T, $v \approx 1$ m/s, $E_p \approx 0.2$ V/m, and the mean number of "free" dipoles formed in water is $N = 2.6 \cdot 10^7$ cm^{-3} $= 2.6 \cdot 10^{10}$ liter^{-1}.

Thus, on the basis of the model of water disinfection adopted by us the number of microorganisms killed should be rather large in percentage terms (see Sec. 3; the maximum initial *E. Coli* value is $N_{E.C.} = 3.4 \cdot 10^6$ liter^{-1}). In this model, water moves relative to the transverse magnetic field in the electric and magnetic fields.

We now try to evaluate (at least in order of magnitude) the relaxation time of "free" dipoles τ_p, i.e., their lifetime in water. For this purpose we assume that τ_p is determined by the characteristic time of approach of two "free" dipoles. The time of attainment of the equilibrium velocity by an ion in water under the action of the external force was shown to be $\sim 10^{-12}$ s [5]. Nearly the same time is needed for dipoles. For this reason the equation of motion of two dipoles closer together is determined by the equality of two forces. They are the frictional force $\vec{F}_{\rm fr}$ and that acting on the dipoles $\vec{F}_g$ [expression (8)]. Taking the dipole to be a sphere (a single water molecule or an associate of 57 H_2O molecules), $\vec{F}_{\rm fr}$ can be written according to the Stokes formula. We have $\vec{F}_{\rm fr} = -6\pi\eta r \vec{v}_g$, where $\eta \approx 1 \cdot 10^{-3}$ N/(s·m) is the viscosity of water, r is the radius of the sphere, and $\vec{v}_g$ is the velocity of its motion. The modulus of the field strength produced by the dipole is given by formula (9). Under the assumption that the magnetic-moment vectors of two dipoles are directed opposite to each other, we have

$$\frac{dE}{dr_0} = -\frac{3p_e}{2\pi\varepsilon_0\varepsilon r_0^4}\ .$$

Let us consider a coordinate system in which one dipole is at the point $x = 0$ while the other is at the point $x = R$. At some instant of time t at the point x we have $v_g = dx/dt$ and $r_0 = R - 2x$. The equation of motion of the dipole $\vec{F}_{\rm fr} = \vec{F}_g$ takes the form

$$6\pi\eta r\frac{dx}{dt} = \frac{3p_e^2}{2\pi\varepsilon_0\varepsilon(R-2x)^4}$$

or

$$\frac{4\pi^2\eta r\varepsilon_0\varepsilon}{p_e^2}(R-2x)^4 dx = dt.$$

Upon integrating this equation over x from 0 to $R/2$ (the dipoles approach each other) and over t from 0 to τ_p, we obtain

$$\tau_p = \frac{2\pi^2\eta r\varepsilon_0\varepsilon}{5p_e^2}R^5. \qquad (10)$$

The parameters entering (10) were already defined above.

In the case where the dipole is associated with a single water molecule, the volume occupied by it is equal to $V_1 = M/A = 18/6.023 \cdot 10^{23} = 2.99 \cdot 10^{-23}$ cm^3, i.e., $r = \sqrt[3]{3V_1/4\pi} = 1.93 \cdot 10^{-10}$ m. In the case where the dipole is associated with an associate of 57 water molecules r increases approximately by a factor of 3.9. For a single water molecule, (10) takes the form

$$\tau_p = 1.417 \cdot 10^{37} R^5. \tag{11}$$

For the case discussed above ($U = 100$ V, $d = 1$ cm) the mean distance between the dipoles is equal to 0.15 μm. Thus, from (11) it follows that $\tau_p = 1.417 \cdot 10^{37}(0.15 \cdot 10^{-6})^5 = 1.08 \cdot 10^3$ s $= 0.3$ hours. This value increases as the number of "free" dipoles per unit volume decreases. By way of example, the mean distance between the "free" dipoles under the experimental conditions of the magnetic treatment of water discussed is $\bar{r} = R = (N)^{-1/3} = (2.6 \cdot 10^{-7})^{-1/3} = 33.8$ μm. According to (11), we have for such a separation between the dipoles $\tau_p = 6.25 \cdot 10^{14}$ s $\approx 2 \cdot 10^7$ years. It is obvious that water does not retain its bactericidal properties for such a long time, otherwise biological life would be impossible on the Planet. Because of this, the relaxation in water is due to not only the attraction between the "free" dipoles but also due to a variety of other processes. Among these are primarily the Brownian motion of particles, convection mixing, and interaction of dipoles with ions.

The discussion of these processes at length is beyond the scope of the present paper. We only emphasize that the time of persistence or that during which water retains its anomalous properties (the bactericidal properties in the case under discussion) exceeds 2 hours. The assessment of this time performed in [1] gives a value of 4 hours.

We now summarize the results obtained in this section.

First and foremost, the model of "free" dipoles formed during the magnetic treatment of water and the action of a constant electric field describes the bactericidal properties of water. Moreover, this model provides a qualitative explanation of the fact that the anomalous properties of water can persist for several hours. The model also explains the fact that the increase in the electric conductivity of water results in the decay of its bactericidal (anomalous) properties because of screening of the magnetic and electric fields. It is not improbable that biological life on Earth, including animal and human life, has its origin in this fact. By way of example, blood has a high electric conductivity. It is also possible that the electric conductivity of human blood and other liquids decreases with age. Because of the action of geomagnetic and geoelectric fields, this, in its turn, can result in various diseases, including cancer and diseases of the immune system. This issue invites further investigation.

It should be also noted that the "free" dipoles in which vicinity the electric field strength is high can strongly affect the physical properties of water. Among the latter are those listed in the Introduction to this paper.

One more important issue is worthy of notice. The energy consumption in the magnetic (with permanent magnets) and electric treatment of water is virtually nil. Thus, these methods, used particularly for water disinfection, offer substantial advantages over any reagentless techniques.

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