

## THE INFLUENCE OF ELECTRIC FIELD PARAMETERS AND TEMPERATURE OF HYDROSOLS OF METALS' PLASMA- EROSIVE PARTICLES ON THEIR RESISTANCE AND PERMITTIVITY

Nataliya Shydlovska, Serhiy Zakharchenko, Oleksandr Cherkaskyi

Institute of Electrodynamics of the National Academy of Science of Ukraine, Kyiv, Ukraine

snzakhar@bk.ru

© Shydlovska N., Zakharchenko S., Cherkaskyi O., 2014

**Abstract:** The experimental dependences of electrical resistivity and real and imaginary components of relative permittivity of metals' hydrosols on their temperature as well as on applied electric field and its frequency have been investigated. Approximants for those dependences have been offered and their optimal coefficients have been calculated for wide range of arguments' values. Range constraints of electric field intensity and its frequency as well as solutions' temperatures have been recommended in order to significantly diminish the electrochemical effect of discharge pulses in a water-submerged metal granules' layer in the course of their plasma-erosive processing.

**Key words:** electric field intensity, electric field frequency, resistivity and permittivity of hydrosols.

### 1. Introduction

The method of plasma-erosive processing of biologically-active metal granules (*Ag, Cu, Zn, Fe, Mn, Co, Mo*) submerged in a bidistillate is currently one of the most effective techniques used for producing their sedimentation-resistant hydrosols and their further utilization in crop and livestock farming and medical industry [1, 2]. Decreasing of the size of dispersion phase particles, increasing of their electro-kinetic potential, and increasing of dispersion phase resistivity contribute to hydrosols' resistance to aggregation and sedimentation [1, 3, 4].

In the course of plasma-erosive processing of dispersion phase - as a result of emergence (in the presence of electric current) of disperse particles and metal ions - a considerable decreasing of its electric resistivity is observed [3]. That fact causes current's redistribution through the liquid and plasma channels, which significantly influences the hydrosols' resistance to aggregation and sedimentation. It is impossible to find optimum conditions for producing such hydrosols without analysis of electromagnetic phenomena both in plasma channels between the metal granules surfaces and in the surrounding liquid.

A physical model and an electrical equivalent circuit representing a layer of metal granules submerged in a liquid were proposed in [5, 6]. However, they do not

take into account the influence of electric field parameters and hydrosols' temperature on their electric properties. The influence of electrostatic field intensity and hydrosols' temperature on their specific conductivity was already discussed [3]. **The purpose of this work** is research of the influence of electric field intensity and its frequency as well as hydrosols' temperature on their electrical resistivity and dielectric permittivity.

### 2. Research technique, equipment, materials

To achieve the objective, several direct experiments have been conducted. Liquids under study, techniques and equipment for investigation of their DC properties were described in details [3]. Totally 11 liquids of different extent of purification and their solutions (corresponding to basic types of liquids used for producing metals' hydrosols) have been investigated. The denotations used in Table 1 have the following meaning: *H<sub>2</sub>O c* – is tap water, *H<sub>2</sub>O d* – is distillate, *H<sub>2</sub>O b* – is bidistillate, *Cu i d0* – is fresh solution of cuprum ions in distillate, *Cu i d7* – is 7-day solution, *Cu p d* – is colloidal solution of plasma-erosive cuprum particles in distillate, *Al p d* – is colloidal solution of plasma-erosive aluminium particles in distillate, *Ag p b* – is colloidal solution of plasma-erosive argentum particles in bidistillate, *Ag p + Cu i b* – is colloidal solution of plasma-erosive argentum particles and cuprum ions in bidistillate. The concentration of dispersion phase and dissolved impurities does not exceed 0,1 g/l in all the solutions.

Fig. 1 depicts electric circuit for measuring the hydrosols' resistivity and dielectric permittivity components under sinusoidal current, and Fig. 2 shows a photograph of the measuring stand. For heating the hydrosols in the measurement cell without changing their chemistry a fan heater has been utilized (it can be seen in Fig. 2 behind the measurement cell). Temperature control in the measurement cell is performed by means of a spirit thermometer. To avoid measurement errors caused by uneven heating of the measurement cell, recording of the hydrosols' electro-physical parameters in their dependency on temperature has been

performed during periods of their slow self-cooling after full completion of their heating procedure.

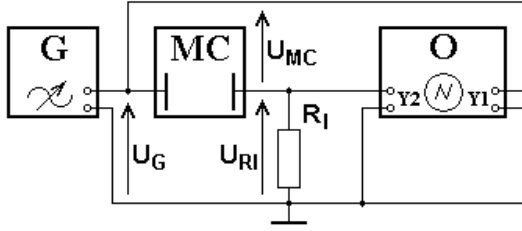


Fig. 1. Circuit for measuring the hydrosols' electro-physical parameters at sinusoidal current.

The denotations used in Fig. 1 have the following meaning:  $G$  – is sinusoidal voltage generator of controlled frequency and amplitude;  $U_G$  – is generator output voltage;  $MC$  – is measurement cell with a hydrosol under investigation; which has a form of a rectangular parallelepiped with the width of cuprum electrodes  $b_L=24$  mm, their height  $h_L=76$  mm, the inter-electrodes distance  $l_L=52$  mm;  $U_{MC}$  – is measurement cell output voltage;  $O$  – is oscillograph;  $R_i$  – is resistance-type current transducer;  $U_{Ri}$  – is current transducer voltage. Such parameters are optimal for producing metals' hydrosols [1, 3, 6].

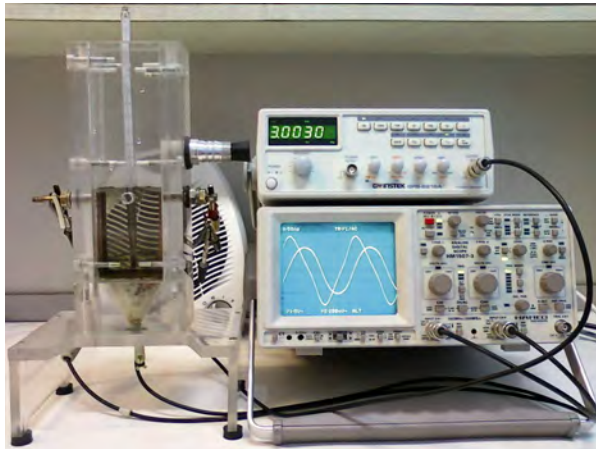


Fig. 2. The stand for measuring the hydrosols electro-physical parameters at sinusoidal current.

The amplitude of measurement cell voltage  $U_{MCm}$  (Fig. 1) can be calculated on the basis of the measured amplitude of generator output voltage  $U_{Gm}$ , the measured amplitude of current transducer voltage  $U_{Rlm}$  and their phase difference  $j_G$  as follows:

$$U_{MCm} = \sqrt{U_{Gm}^2 + U_{Rlm}^2 - 2U_{Gm} \cdot U_{Rlm} \cos j_G} \quad (1)$$

The angle of phase displacement between the measurement voltage and the current can be obtained as follows:

$$j_{MC} = j_G + \arcsin(U_{Rlm} \sin j_G / U_{MCm}) \quad (2)$$

Taking into account the geometrics of the measurement cell as well as (1) and (2), one can calculate the active component of specific impedance of the hydrosols under investigation at sinusoidal current:

$$r_{FAC} = (U_{MCm} \cdot b_L \cdot h_L) / (\text{Re}[I_{MCm}] \cdot l_L) = (U_{MCm} \cdot b_L \cdot h_L) / (I_{MCm} \cdot l_L \cdot \cos j_{MC}) \quad (3)$$

where  $I_{MCm}$ ,  $A$  is the measurement cell current amplitude.

As a result of applying the sinusoidal voltage to the measurement cell electrodes, such kinds of current flow arise: 1) loss current  $I_{FR0}$  due to conductivity, that does not depend on frequency and can be found at DC voltage on the electrodes; 2) displacement current  $I_{FCQ}$  due to a hydrosol capacitance that depends on the real (active) component of a hydrosol permittivity  $\text{Re}[e_z]$ ; 3) relaxation losses current  $I_{FR}$  due to the imaginary (reactive) component of a hydrosol permittivity  $\text{Im}[e_z]$ .

In practice for the hydrosols under investigation, the loss current due to conductivity is approximately equal to the full current at low frequency (less than 50 Hz). The possibility to measure a current at a low frequency instead of measuring a direct current considerably simplifies the experiment procedure. Taking into account the foresaid facts, an equivalent hydrosol's electric circuit at sinusoidal current consists of a resistance  $R_{FDC}$  (representing losses due to conductivity) and a non-ideal capacitor  $C_F$  with dielectric relaxation losses, connected in parallel. The non-ideal capacitor is represented, in its turn, by parallel connection of capacitance  $C_F$  and resistance  $R_{FR}$  (simulating relaxation losses in the dielectric). For such circuit, the sinusoidal current  $I_{FC}$  of the non-ideal flat capacitor can be written in the form:

$$I_{FC} = -\sqrt{-1} \cdot 2\pi f U_{MCm} b_L h_L e_0 (\text{Re}[e] + \sqrt{-1} \cdot \text{Im}[e]) / l_L, \quad (4)$$

where  $e_0=8,85 \cdot 10^{-12}$  F/m is absolute vacuum permittivity. The formula takes into account the dependence of the capacity on geometrics and dielectric properties and the dependence of the reactance on frequency  $f$ .

The imaginary part (4) represents the hydrosol's displacement current; its effective value can be calculated as product of effective value of the full measurement cell current  $I_{MC}$  and sine of the angle of phase displacement  $j_{MC}$  between the current vector and voltage vector of the measurement cell. Therefore, the real part of the relative permittivity can be calculated as follows:

$$\text{Re}[e] = \frac{I_{MCm} \cdot \sin j_{MC} \cdot l_L}{2\pi f U_{MCm} \cdot e_0 \cdot b_L \cdot h_L} = \frac{tg j_{MC}}{2\pi f e_0 r_{FAC}} \quad (5)$$

The real part (4) represents the active current of dielectric relaxation losses  $I_{FR}$  arising due to imaginary part of the hydrosol's relative permittivity  $\text{Im}[e]$ . That

current is in phase with the loss current (arising due to conductivity)  $I_{FR0}$  and their sum forms the active component of the measurement cell current that is expressed as  $I_{MCm} \cdot \cos j_{MC}$ :

$$\begin{aligned} I_{MCm} \cos j_{MC} &= I_{FR0m} + I_{FRm} = \\ &= \frac{U_{MCm}}{R_{FDC}} + 2pfU_{MCm} \frac{b_L h_L}{l_L} e_0 \operatorname{Im}[e] \end{aligned} \quad (6)$$

where  $R_{FDC}$ ,  $\Omega$  is the resistance of the hydrosol in the measurement cell at direct current.

Solution of (6) and taking account of (3) gives us imaginary part of the hydrosol's permittivity:

$$\begin{aligned} \operatorname{Im}[e] &= \frac{I_{MCm} \cos j_{MC} - U_{MCm}/R_{FDC} \cdot l_L}{2pfU_{MCm} b_L h_L e_0} = \\ &= \frac{1/R_{FAC} - 1/R_{FDC}}{2pf b_L h_L e_0} l_L = \frac{1/r_{FAC} - 1/r_{FDC}}{2pf b_L h_L e_0}, \quad (7) \\ &= \frac{r_{FDC} - r_{FAC}}{2pfe_0 r_{FDC} r_{FAC}} \end{aligned}$$

where  $R_{FAC}$ ,  $\Omega$  is the active component of hydrosol's impedance at sinusoidal current.

For practical purposes to simplify the experiment procedure, we have replaced the hydrosol's electrical resistivity (arising due to its conductivity) at direct current by the hydrosol's electrical resistivity modified at low frequency (1 Hz).

### 3. Results of experiments conducted at direct current and their discussion

The dependences of electrical resistivity (at direct current) of bidistillate ( $H_2O$  b), argentum hydrosol in bidistillate ( $Ag p$  b) and argentum hydrosol in bidistillate with cuprum ions ( $Ag p + Cu i$  b) on the measurement cell voltage at room temperature and high temperature  $T$  are shown in Fig. 3 a) and b), respectively. Experimental results for other liquids are similar in appearance and, thus, not shown. If we assume that electric field is uniform within the whole hydrosol's volume, it can be calculated using the voltage between the electrodes as  $E = U_{MC}/(e \cdot l_L)$ . In our case, at the voltage  $U_{MC} = 100$  V the electric field is  $E = 23.74$  V/m.

It can be seen in Fig. 3 that electrical resistivity for all the objects under investigation tends to decrease when electric field increases. Especially clearly it can be observed by low values of voltage applied to the measurement cell electrodes (below 200 V), which corresponds to intensity  $E = 47.48$  V/m of quasi-uniform electric field in the cell. The more pure and cold water is, the more clearly the considerable decrease in the electrical resistivity is observed even at high intensity of electric field.

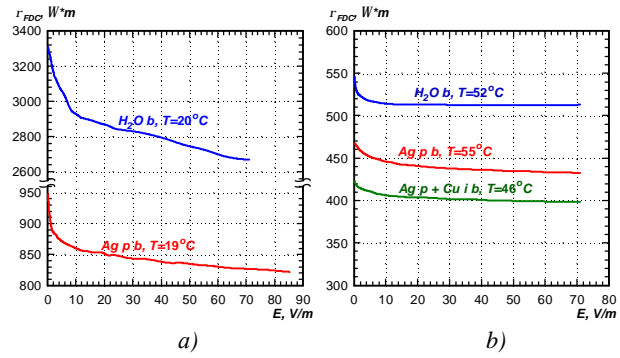


Fig. 3. Dependences of electrical resistivity of bidistillate and Ag-hydrosols on the applied electric field at a) room temperature and b) high temperature.

The observed decrease in the electrical resistivity of the objects under investigation accompanying the electric field intensity increase can be explained by following reasons. Firstly, by the presence of electrode potentials of soluble electrodes [7], whose influence is especially evident at low voltages. Secondly, by possible decrease in degree of hydration of the ions [7] in strong electric fields, that leads to increase in their mobility. Thirdly, by possible increase in dissociation degree [7] of the electrolytes under investigation in strong fields, that leads to increase in concentration of free charge carriers.

The most appropriate approximation function for nine solutions out of eleven ones (i.e. except distillate and colloidal solution of plasma-erosive aluminium particles in distillate) is a function comprising hyperbole raised to a rational index of power:

$$r_{FDC}(U)_N = r_{FDC0} + r_{FDC1N} / U^{a_{F2N}}, \quad (8)$$

where  $r_{FDC0}$ ,  $\Omega \cdot m$  is the approximation function coefficient having physical meaning of a constant component of electrical resistivity, defining its value at voltages below breakdown of liquid;  $r_{FDC1N}$ ,  $\Omega \cdot m \cdot a_{F2N} \sqrt{V}$  is the approximation function coefficient whose physical meaning is an increase in electrical resistivity at a voltage of 1 V as compared to its value at high voltages;  $a_{F2N}$  is the power of approximation function.

The most appropriate approximation function of electrical resistivity dependence on applied DC voltage for distillate and colloidal solution of plasma-erosive aluminium particles in distillate is a function comprising exponential:

$$r_{FDC}(U)_E = r_{FDC0} + r_{FDC1E} \cdot \exp[-U/U_{FE}], \quad (9)$$

where  $r_{FDC1E}$ ,  $\Omega \cdot m$  is the approximation function coefficient whose physical meaning is an increase in

electrical resistivity at a voltage of 0 V as compared to its value at high voltages;  $U_{FE}$  is the approximation function coefficient that is equal to the voltage increase accompanied by the decrease in the second term (9) by a factor of  $e$ .

To find the approximation function coefficients (8), (9) that are appropriate for the whole range of argument's change a criterion of minimum value of integral residual parameter  $b_2$  was developed [8]; the parameter is calculated as one-half of the sum of two terms: firstly, relative standard deviation of  $N$  approximated values  $y_{Aj}$  from their experimental counterparts  $y_j$

$$u[y, y_A] = 100\% \cdot s[y, y_A] / M[y] = \\ = 100\% \cdot \sqrt{N \cdot \sum_{j=1}^N (y_j - y_{Aj})^2} / \sum_{j=1}^N y_j ;$$

secondly, average sum of modules of the relative errors

$$d[y, y_A] = \frac{100\%}{N} \sum_{j=1}^N |(y_j - y_{Aj}) / y_j| ;$$

i.e.

$$b_2[y, y_A] = (u[y, y_A] + d[y, y_A]) / 2 \quad (10)$$

For the solutions under investigation (except distillate and colloidal solution of plasma-erosive aluminium particles in distillate) the values of the integral parameter of discrepancy  $b_2$  (10), obtained by approximation of the electrical resistivity dependence on the applied voltage using the discussed function (8), fall within the range from 0.13 % to 1.22 %. For two remaining solutions the value  $b_2$  equals to 5.95 % and 6.1 %, respectively. However, if the above-mentioned function (9) is used for approximation, the values  $b_2$  fall within the range from 0.25 % to 2.84 %. The obtained values of  $b_2$  serve as verification that the proposed formulae (8), (9) provide high approximation accuracy for the dependences in fairly wide range of the argument's change.

It should be noted that the application of the approximation formulae (8), (9) for analytical description and analysis of transients in circuits (comprising the elements under investigation) of the second and higher orders is complicated [9]. The values of the coefficient  $a_{F2N}$  (8) obtained as a result of approximation calculations fall in the range from 0.02 (for colloidal solution of plasma-erosive Ag-particles in bidistillate at the temperature  $T=55^\circ\text{C}$ ) to 0.72 (for tap water at room temperature). To simplify analytical computation of transients in circuits comprising the

elements, the discrepancy error has been studied for the event of applying the approximation function (8) with fixed values of the parameter  $a_{F2N}=0.5$  and  $a_{F2N}=1$ .

As a result of performed calculations for the solutions under investigation, except tap water with relatively high concentration of different ions, the value of index of power of the approximation function (8) power for  $a_{F2N}=0.5$  is more suitable than 1. Table 1 shows optimal values of approximation function (8) coefficients (for  $a_{F2N}=0.5$ ) obtained for all solutions under investigation at DC in compliance with  $\min[b_2]$ -criterion for approximation of their electrical resistivity dependences on the applied voltage as well as the obtained values of the integral parameter of discrepancy  $b_2$ .

Table 1

**Approximation function parameters  
for the solutions electrical resistivity dependences  
on the voltage on the electrodes in the case  
of applying a hyperbole raised to the index  
of power -0,5**

No.	Type of solution	$r_{FDC0}$ , $\Omega \cdot m$	$r_{FDC10}$ , $\Omega \cdot m \cdot \sqrt{V}$	$b_2[r_F, r_{FA}]$ , %
1.	$H_2O c, T=23^\circ\text{C}$	24,32	14,4	2,2
2.	$H_2O d, T=24^\circ\text{C}$	385,21	1097,68	13,7
3.	$Cu i d0, T=24^\circ\text{C}$	133,51	117,24	2,62
4.	$Cu i d7, T=24^\circ\text{C}$	340,87	608,24	1,79
5.	$Cu p d, T=23^\circ\text{C}$	338,05	139,33	1,51
6.	$Al p d, T=23^\circ\text{C}$	165,87	273,36	12,3
7.	$H_2O b, T=19^\circ\text{C}$	2774,87	894,15	2,86
8.	$H_2O b, T=52^\circ\text{C}$	509,72	36,46	1,45
9.	$Ag p b, T=19^\circ\text{C}$	833,32	142,68	0,91
10.	$Ag p b, T=55^\circ\text{C}$	435,97	52,12	1,06
11.	$Ag p + Cu i b, T=46^\circ\text{C}$	400,24	33,45	0,66

As one can see from Table 1, approximation errors in case of applying the function (8) with  $a_{F2N}=0,5$  does not exceed 3% for all solutions under investigation except No. 2 and No. 6, which is quite sufficient for engineering analysis, and the values of the coefficient  $r_{FDC0}$  increase accordingly to increase in dispersion degree of purification and decrease in solution temperature.

The dependences of electrical resistivity on temperature at DC for several solutions under investigation were given in [3]. The dependences for other solutions in case of the applied voltage range from 1 V to 300 V are similar as in [3]. It was shown that electrical resistivity dependence on temperature for all solutions

under investigation could be with high accuracy ( $b_2 < 3\%$ ) represented by the known formula [7]:

$$r(T) = r_{T_{25}} / (1 + a_{T1}(T - T_{25})), \quad (11)$$

where  $r_{T_{25}}$ ,  $\Omega \cdot m$  is electrical resistivity of highly diluted solutions at temperature  $T_{25}=25^\circ C$ ;  $a_{T1}$ ,  $1/^\circ C$  is temperature coefficient of solution resistivity.

Our research shows that the temperature coefficient  $a_{T1}$  in (11) increases with decrease in ion concentration in water, i.e. with increase in degree of purification. Its averaged values for the solutions under investigation are: bidistillate –  $0.0256\ 1/^\circ C$ , distillate –  $0.021919\ 1/^\circ C$ , colloidal solution of plasma-erosive cuprum particles in distillate –  $0.02084\ 1/^\circ C$ , 7-day saturated solution of plasma-erosive cuprum particles in distillate –  $0.01502\ 1/^\circ C$ , solution of plasma-erosive Ag-particles in bidistillate –  $0.0136\ 1/^\circ C$ , fresh saturated solution of cuprum ions in distillate –  $0.009236\ 1/^\circ C$ , fresh solution of ions and plasma-erosive aluminium particles in distillate –  $0.008675\ 1/^\circ C$ . This can be explained by the fact that in the case of weak concentration of highly mobile carriers (i.e ions of dissolved impurities) electrical conductivity of water is caused mainly by ions  $H^+$  и  $OH^-$ . Their concentration depends on dissociation constant that, in its turn, depends on temperature [7].

The change of voltage on electrodes within the said range practically does not influence the temperature coefficient of the solutions under investigation; only for some solution its slight upward trend is observed in the course of voltage increase. On the other hand, for all solutions under investigation, the voltage increase leads to significant decrease in electrical resistivity  $r_{T_{25}}$  at temperature  $25^\circ C$ .

**4. Results of experiments conducted at alternative current and their discussion**

Fig. 4 shows dependences of electrical resistivity  $r_{FAC}$  (3), of real  $Re[e]$  (5) and imaginary  $Im[e]$  (7) components of dielectric permittivity on applied voltage frequency for colloidal solution of plasma-erosive argentum particles in bidistillate at temperature  $T=20^\circ C$ . The dependences are to a large extent dictated by corresponding dependences for pure bidistillate. We can observe that, in low-frequency band, the electrical resistivity of argentum hydrosols is less that the latter of initial bidistillate by 18.5 % at voltage amplitude  $U_m=1\ V$  by 3.86 % at voltage amplitude  $U_m=10\ V$ ; in high-frequency band, the electrical resistivity of argentum hydrosols is less that the latter of initial bidistillate by, on the average, 2.6 % at all investigated voltage amplitudes.

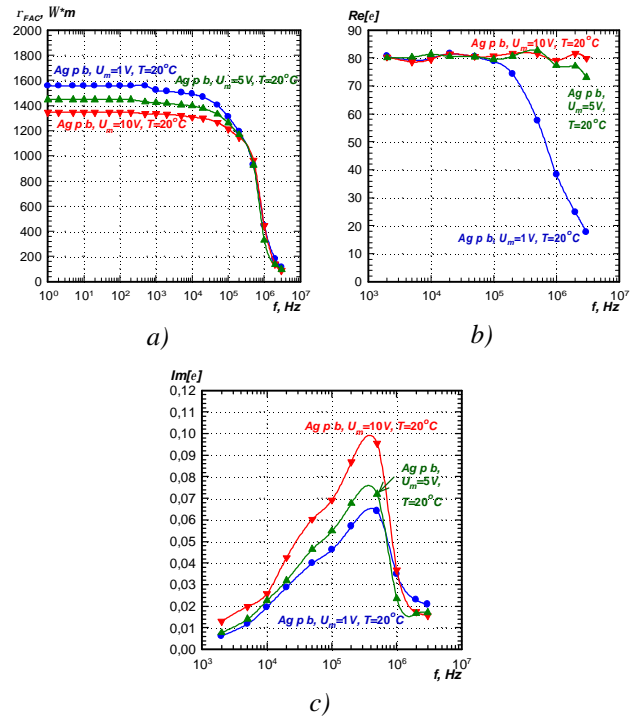


Fig. 4. Dependences of a) electrical resistivity, b) real component of relative permittivity, c) imaginary component of relative permittivity on applied voltage frequency for bidistillate Ag-hydrosols.

For colloidal solution of plasma-erosive argentum particles in bidistillate the increase in temperature up to  $T=50^\circ C$  leads, in low-frequency band, to a decrease in its resistivity by a factor of 2.89 at  $U_m=1\ V$  and by a factor of 2.83 at  $U_m=5\ V$  and  $10\ V$ ; on the other hand, in middle- and high-frequency band, it leads to an increase in imaginary component of permittivity by a factor of 1.1. Other parameters are only slightly influenced by such temperature increase. For pure bidistillate, such temperature increase leads, in low-frequency band, to a decrease in its resistivity by a factor of 3.31 and in middle- and high-frequency band, it leads to an increase in imaginary component of permittivity by a factor of 1.07. It should be noted that electrical resistivity of pure bidistillate is larger than the latter of corresponding argentum colloid by a factor of 1.23; imaginary component of permittivity of pure bidistillate is less than the latter of corresponding argentum colloid by a factor of 1.22.

One can see from Fig. 4,a) and experimental results that an increase in frequency of the applied sinusoidal voltage leads to decrease in electrical resistivity of all solutions under investigation (distillate, bistillate, Ag in bidistillate at temperature  $20^\circ C$  and  $T=50^\circ C$ ). Up to frequency  $f=100\ kHz$  that decrease is not significant (from 8 to 20 %), after  $500\ kHz$  it amounts to 40 %, and at frequency  $3\ MHz$  it exceeds 90%. It should be noted that, the purer the solution is and the lower its

temperature is, the more significant a decrease in its resistivity due to increase in the frequency is (Fig. 4).

The phenomenon of decreasing of water and water solutions' electrical resistivity accompanying an increase in frequency of applied sinusoidal voltage is explained by increasing of active component of dielectric losses due to repolarization [10]. Among different types of dielectric losses in polar liquids (including water), dipole-relaxation losses are those most substantial in RF band [10].

At relatively low frequencies (up to 10 kHz in our case) the decrease in electrical resistivity and real component of relative permittivity (Fig. 4,b) as well as increase in its imaginary component (рис. 4,c) are not important. This fact allows us to conclude that average equivalent time for orientation of water polar molecules and molecules of other polar impurities in sinusoidal electric field in the explored conditions is significantly less than half-period of the applied sinusoidal voltage, in our case 50 μs. Taking into account that a local extremum of imaginary component of relative permittivity is observed by frequencies close to 500 kHz (Fig. 4,c), we may conclude that average equivalent time for orientation of water polar molecules and molecules of other polar impurities in sinusoidal electric field under the explored conditions is of about 1 μs.

In the case of further frequency increasing the lag in orientation of water molecules in sinusoidal electric field in accordance with its vector increases. It means that the number of molecules managing to rotate in compliance with changes in an external electric field (i.e the number of molecules whose electric field is aligned along an external electric field) is decreasing. As a consequence, in that frequency band (0.5–3 MHz) real and imaginary components of relative permittivity decrease and descent rate of water electrical resistivity drops down (Fig. 4).

At low electric field intensity, its high frequency, high water temperature, and low degree of water purification one can observe some discrepancy between experimental data and P. Debye theory [10]. Namely, P. Debye theory does not predict the existence of a local extremum of imaginary component of relative permittivity of the solutions under investigation at frequencies close to equivalent orientation frequency of water polar molecules and molecules of other polar impurities in sinusoidal electric field (about 500 kHz) (Fig. 4,c). Disadvantages of P. Debye theory regarding analysis of permittivity dependence of polar liquids and gases on applied voltage frequency was discussed in [11] and explained by neglecting internal electric fields, which leads to poor accuracy in high-frequency band as well as by existence of polar impurities.

Although there is a lot of dielectric polarization theories and formulae for its dependence on frequency

(P. Langevin-P. Debye, P. Debye, H. Lorentz - L. Lorenz) [10], we failed to find mathematical approximation of those dependences for water of low degree of purification and for its colloidal solutions due to complexity and peculiarity of such a problem. That is why it is reasonable to utilize for analysis of electromagnetic transients in such media the values of electric resistivity, real and imaginary components of relative dielectric permittivity obtained experimentally for an appropriate frequency band (Fig. 4).

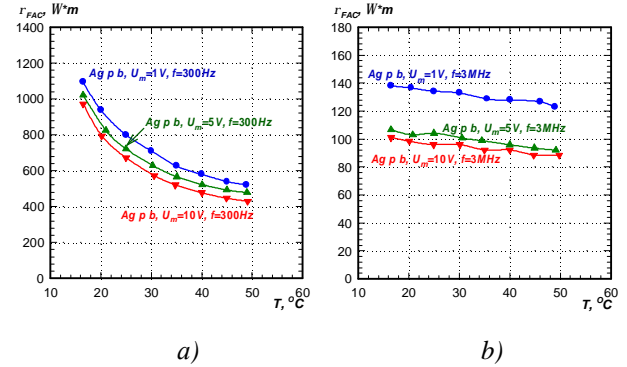


Fig. 5. Dependences of electrical resistivity on temperature for colloidal solution of plasma-erosive Ag-particles in bidistillate at current frequency a) 300 Hz and b) 3 MHz.

Fig. 5 shows dependences of electrical resistivity for colloidal solution of plasma-erosive Ag-particles in bidistillate on temperature at frequency 300 Hz and 3 MHz. The dependences of electrical resistivity on temperature for colloidal solution of plasma-erosive Ag-particles in bidistillate at low frequency alternative current are fairly similar to those at direct current [3]. At high frequencies those dependences are hardly observed.

Table 2 comprises values of temperature coefficient  $a_{T1}$  (11) and electric resistivity  $r_{T25}$  at temperature 25 °C for pure bidistillate and corresponding Ag-colloid obtained on the basis of experimental data for applied voltages frequency  $f=300$  Hz and 3 MHz and amplitudes  $U_m=1$  V, 5 V and 10 V. The values have been obtained using the criterion  $\min[b_2[r_F, r_{FA}]]$  (10).

Table 2

**Values of temperature coefficient and electric resistivity for bidistillate and corresponding Ag-colloid**

$U_m, V$	Bidistillate				Ag in bidistillate			
	$f=300$ Hz		$f=3$ MHz		$f=300$ Hz		$f=3$ MHz	
	$r_{T25}, \Omega \cdot m$	$a_{T1}, 1/^\circ C$	$r_{T25}, \Omega \cdot m$	$a_{T1}, 1/^\circ C$	$r_{T25}, \Omega \cdot m$	$a_{T1}, 1/^\circ C$	$r_{T25}, \Omega \cdot m$	$a_{T1}, 1/^\circ C$
1	1059	0,0242	157	0,00372	798,5	0,0223	134,2	0,00388
5	963	0,0244	129	0,00387	720,1	0,0211	104,2	0,00345
10	920	0,0247	123	0,00427	671,1	0,0233	96,1	0,00337

As it can be seen from Table 2 and above-mentioned results, the values of temperature coefficient and electrical resistivity for distillate, bidistillate, and Ag-colloid in bidistillate at direct current are close to those at alternative current of low frequency. Moreover, the values increase when conductivity of the discussed systems decreases.

Values of temperature coefficient and electrical resistivity in high-frequency band (3 MHz) are one order less than those in low-frequency band (300 Hz). This is explained by the fact that at high frequencies active losses due to dipole-relaxation polarization contribute to hydrosol's conductivity much more than ion conductivity (that is highly influenced by temperature) does. In all cases electrical resistivity dependence on temperature for the discussed liquids and hydrosols can be described with high accuracy by the dependence (11), but values of its parameters depend both on water degree of purification and current frequency.

Fig. 6 shows dependences of a) real and b) imaginary components of relative permittivity on temperature for colloidal solution of plasma-erosive Ag-particles in bidistillate. Corresponding dependences for pure bidistillate are similar in appearance.

It can be seen from Fig. 6 that the decrease in real component and increase in imaginary components of permittivity for colloidal solution of plasma-erosive Ag-particles in bidistillate accompanying the temperature increase is observed to the largest extent at low voltages, which is explained by peculiarities of its dipole-relaxation polarization.

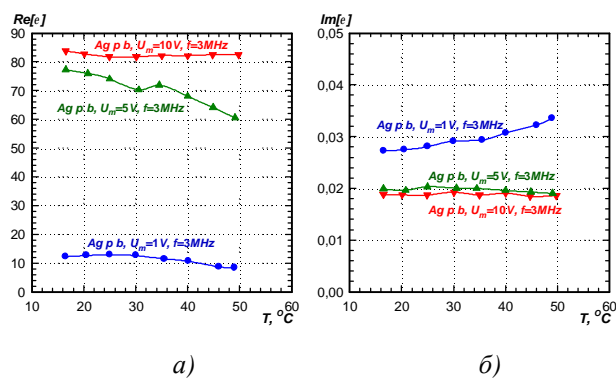


Fig. 6. Dependences of a) real component of relative permittivity and b) imaginary component of relative permittivity on temperature for colloidal solution of plasma-erosive Ag-particles in bidistillate.

## 5. Conclusions

1. As a result of direct experiments, for colloidal and true solutions of plasma-erosive particles and ions of metals their dependences of electrical resistance as well as real and imaginary components of permittivity on

electric field intensity and its frequency as well as on their temperature have been defined. On the basis of the experimental dependences the electrical parameters of an equivalent RC-circuit representing the working liquid in systems of plasma-erosive processing of metal granules have been computed for a wide range of change of parameters of discharge pulses.

2. It has been shown that application of a hyperbole raised to an arbitrary index of power for approximation of the electrical resistivity dependences of water metal solutions on electric field intensity provides the best approximation accuracy. It has been explained for which solutions it is possible, for the purpose of simplification of analytical calculation of transients in the solutions, to assume that the index of power equals to 0.5.

3. The application of the electric parameters dependences of the water solutions on their temperature and electric field parameters received at direct current instead of those for sinusoidal current with frequency up to 100 kHz has been justified.

4. With intent to significantly diminish the electrochemical influence of unipolar discharge pulses in a water-submerged metal granules' layer it has been recommended the electric field intensity cutoff value of 25 V/m and the temperature cutoff value of 25 °C. That recommendation has been done owing to nonlinearity of dependences of the electrical resistivity of solutions on their temperature and intensity of applied electric field.

## References

- [1] A. Shcherba, S. Zakharchenko, K. Lopatko, N. Shevchenko, and M. Lomko, "Discharge pulse systems for manufacturing of nanocolloidal solutions of biologically active metals by method of volumetric electrospark dispersion", *Pratsi Instytutu elektrodynamiky NAN Ukrainy*, no. 26, pp. 152–160, 2010. (Russian)
- [2] K. Lopatko, M. Melnychuk, Y. Aftandilyants, E. Gonchar, V. Boretskyi, A. Veklich, S. Zakharchenko, T. Tugay, A. Tugay, and V. Trach, "Obtaining of metallic nanoparticles by plasma-erosion electrical discharges in liquid media for biological application", *Annals of Warsaw University of Life Sciences – SGGW Agriculture*, no. 61, pp. 105–115, 2013.
- [3] S. Zakharchenko, "The influence of intensity of an external electric field and temperature on resistance of hydrosols of metal particles produced by spark erosion", *Pratsi Instytutu elektrodynamiky NAN Ukrainy*, no. 33, pp. 113–120, 2012. (Russian)
- [4] S. Voyutskiy, *Lectures on chemistry of colloids*. Moscow, Russia: Khimiya, 1976. (Russian)

- [5] S. Zakharchenko, "Physical model of the granulated current-carrying medium", *Tekhnichna elektrodynamika*, no. 6, pp. 19–26, 2012. (Russian)
- [6] S. Zakharchenko, "Modeling of dependence of electrical resistivity of granulated conductive media from a pulse current proceeding in them", *Tekhnichna elektrodynamika*, no. 5, pp. 17–27, 2012. (Russian)
- [7] A. Stromberg and D. Semchenko, *Physical chemistry: manual for university students*. Moscow, Russia: Vysshaya shkola, 2001. (Russian)
- [8] N. Shydlovska, S. Zakharchenko, and A. Cherkaskyi, "Nonlinear parametric model of electrical resistance of conductive granulated media for a wide range of applied voltage", *Tekhnichna elektrodynamika*, no. 6, pp. 3–17, 2014. (Russian)
- [9] N. Shydlovska and S. Zakharchenko, "Transients in the RLC-circuit with heterogenous plasma-erosive load", *Tekhnichna elektrodynamika*, no. 3, pp. 3–11, 2014. (Russian)
- [10] P. Pavlov and A. Khokhlov, *Solid-state physics*. Moscow, Russia: Vysshaya shkola, 2000. (Russian)
- [11] G. Skanavi, *Dielectric physics. Weak fields study. Part. I*. Moscow, Russia: GTTI, 1949. (Russian)

**ВПЛИВ ПАРАМЕТРІВ  
ЕЛЕКТРИЧНОГО ПОЛЯ  
ТА ТЕМПЕРАТУРИ ГІДРОЗОЛЕЙ  
ПЛАЗМОЕРОЗІЙНИХ ЧАСТИНОК  
МЕТАЛІВ НА ЇХНІЙ ОПІР ТА  
ДІЕЛЕКТРИЧНУ ПРОНИКНІСТЬ**

Наталія Шидловська, Сергій Захарченко,  
Олександр Черкаський

Досліджено експериментальні залежності питомого електричного опору, дійсної та уявної складових відносно діелектричної проникності гідрозолей металів від їх температури, а також від напруженості та частоти прикладеного електричного поля. Запропоновано функції, що апроксимують ці залежності, та знайдено оптимальні значення їх коефіцієнтів у широкому діапазоні зміни аргументів. З метою

істотного зменшення електрохімічної дії розрядних імпульсів у зануреному у воду шарі металевих гранул при їх плазмоерозійній обробці, рекомендовано діапазони обмеження їх напруженості, частоти, а також температури розчинів.



**Nataliya Shydlovska** – is Principal Research Fellow of the Institute of Electrodynamics of the National Academy of Sciences of Ukraine, Corresponding Member of the National Academy of Sciences of Ukraine (2000). She graduated from National Technical University of Ukraine "Kyiv Polytechnic Institute" (1986). She is the author of more than 100 scientific works. Her research interests are electromagnetic processes in nonlinear and parametric circuits.



**Serhiy Zakharchenko** – is Senior Research Fellow of the Institute of Electrodynamics of the National Academy of Sciences of Ukraine, PhD (2004). He graduated from National Technical University of Ukraine "Kyiv Polytechnic Institute" (1996). He is the author of more than 100 scientific works. His research interests are electromagnetic processes in the systems of plasma-erosive processing of heterogeneous conducting media.



**Oleksandr Cherkaskyi** – is PhD student of the Institute of Electrodynamics of the National Academy of Sciences of Ukraine. He graduated from National Technical University of Ukraine "Kyiv Polytechnic Institute" (2013). His research interests are the transients in nonlinear parametric circuits.