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ON THE FEATURES OF THE INFLUENCE OF IMPURITIES OF THE ELECTRODE MATERIAL ON THE ELECTRICAL CONDUCTIVITY OF THE PLASMA OF PULSE ELECTRICAL DISCHARGE IN WATER

V.V. Hladkovskyi[1], V.G. Panchenko[2], P.V. Porytskyi[2], O.A. Fedorovych[2], L.M. Voitenko[2], L.M. Sviata[2]

[1]National Academy of Sciences of Ukraine, Kyiv, Ukraine;
[2]Institute for Nuclear Research of NASU, Kyiv, Ukraine

E-mail: lsvjat@kinr.kiev.ua

The influence of impurities of the electrode material on the electrical conductivity of pulsed discharge plasma in water is considered. Experimental studies of electrical conductivity were conducted and calculations were performed based on the Grade method of moments. It is shown that a small amount of metal and carbon impurities can significantly change the value of the plasma electrical conductivity coefficient compared to the case of pure water vapor. It is found that metal and carbon impurities can cause both an increase and a decrease of the plasma electrical conductivity, which is related to the processes of interparticle collisions and the presence of clusters.

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INTRODUCTION

Pulsed electric discharges are widely used in energetics, metallurgy, oil and gas industry and shipbuilding [1-7]. At the same time, such discharges take place in electric technological processes, such as electric welding, stamping, casting cleaning and rock crushing. In addition, interest in studying such discharges is growing due to the development of new technologies related to waste processing, water purification and new directions of hydrogen energy researches [3-7].

The plasma of discharges in water contains not only dissolved substances, but also the material of the electrodes and conductors through which current is supplied to the plasma or which are used to initiate discharges. These impurities can significantly affect the properties of the hydrogen-oxygen plasma, causing changes in the current distribution and energy release in the discharge channels, as well as affecting the formation of the structure and dynamics of the discharge chanel development [7, 8].

In a multicomponent plasma medium, due to the large number of different types of interparticle interactions and transport processes, the character of processes is significantly complicated. The properties of plasma with impurities of electrode materials significantly depend on its composition [8-12]. The characteristic features of the transport properties of thermal plasma of water vapor without impurities are considered in [8-10]. The appearance of impurities in the electrode material and evaporated conductors can lead to an increase in the conductivity and energy density in the plasma due to an increase in the density of charge carriers due to the significantly lower ionization potentials of metal atoms compared to atoms in the aqueous medium. On the other hand, for low-temperature plasma, the processes of interaction of electrons with neutral particles are important [11, 12]. After all, these processes can also affect the electrical conductivity, so it is necessary to pay special attention to such processes.

The aim of this work is to study the influence of the physical characteristics of the multicomponent plasma of pulsed discharges in the aqueous mixture with vapors of the electrode material (metals and carbon) on the electrical conductivity of the plasma.

ELECTRICAL CONDUCTIVITY OF MULTICOMPONENT WATER VAPOR PLASMA WITH IMPURITIES

Consider a dense plasma in a state of local thermodynamic equilibrium (LTE) (see [10-12]). Due to the high concentrations of neutrals and electrons, collision processes in such a plasma are much more significant than particle transfer processes and radiation processes in the local volume. For a multicomponent low-temperature plasma in which LTE is maintained, the component composition can be calculated based on the law of effective masses, which also reflects the reaction processes. In particular, the electron concentration at a given discharge point is related to the concentrations of ions and neutral particles by the Saha equations.

Determining the plasma composition allows us to calculate the transport properties of the plasma. In the calculations, we will use the Grad momentum method [12-14]. It should be noted that in [12] the applicability of the Grad method to problems of partially ionized plasma was shown and a comparison was made with the more common used the Chapman-Enskog method [15,16].

Both methods are based on the Chapman-Cowling integral formalism [14-16]:

$$\Omega_{\alpha\beta}^{lr} = \left(\frac{kT}{2\pi\mu_{\alpha\beta}}\right)^{\frac{1}{2}} \int_0^\infty \varsigma^{2r+3} e^{-\varsigma^2} Q_{\alpha\beta}^{(l)}(\varsigma) d\varsigma, \quad (1)$$

where k is the Boltzmann constant, T is temperature, $\mu_{\alpha\beta}$ is the total mass of particles of varieties α and β, who are involved in the collision, $\varsigma=(\mu_{\alpha\beta}/2kT)^{(1/2)}g$, g is the relative velocity. The transport cross section of order l is defined as $Q^l_{\alpha\beta}(g) = 2\pi \int_0^{\pi} \sigma_{\alpha\beta}(g,\chi)(1-cos^l\chi)\,sin\,\chi\,d\chi$, where χ is an scattering angle, $\sigma_{\alpha\beta}(g,\chi)$ is the differential scattering cross section.

In the thirteenth moment (13M) approximation of the Grade method, the translational transport coeff-?cients are calculated as the sum of the effective coefficients for each type of particle. And the effective coefficients themselves are calculated based on a certain combination of Chapman-Cowling integrals (1). It should be noted that the electrical conductivity of a dense low-temperature plasma is determined mainly by electrons due to the high density of the plasma medium. The calculation of the electronic transport coefficients requires the use of higher approximations. Thus, the electrical conductivity σ can be written [12,14,16] as

$$\sigma = \frac{3}{2} n_e^2 e^2 \left(\frac{2\pi}{m_e kT}\right)^{\frac{1}{2}} \frac{|q'|}{|q|}, \qquad (2)$$

where m_e is an electron mass, n_e is the electron density in plasma, and the elements of the determinants q,q' are functions of the above Chapman-Cowling integrals (1) (see, for details [12, 14, 16]).

From formula (2) it follows that the electrical conductivity of low-temperature plasma mainly depends on the plasma density (the number of charge carriers) and the processes of interparticle interaction (the frequency of collisions). Since metal atoms have a much lower ionization potential compared to the atoms of the aqueous medium, the invasion of metal atoms into the discharge channel causes an increase in the plasma density, which is a clear factor in the increase in electrical conductivity. On the other hand, the chara-?teristics of interparticle collisions can be complex and these processes can generally cause both an increase and a decrease in the electrical conductivity of the plasma. The conditions for the latter will be considered in more detail below.

The most detailed study of electron scattering at low energies was performed on a copper atom [17-19]. Various models of the electron-atom collision cross section for copper and the results of its usage in modeling gas-discharge plasma are discussed in [18]. The following models of the low-energy electron scattering cross section on a copper atom are that the most common and applicable resonance model [17], characterized by the presence of resonance near 0.1 eV, and the non-resonance model without such resonance [18]. However, later calculations were made using a new alternative model [19], which is also characterized by the presence of resonance, but with a shift towards higher energies.

For calculations of the plasma of a mixture of water vapor and copper, we use the following set of 16 particles: e^-, H_2O, H_2O^+, H_2, H_2^+, OH, OH^+, O_2, O_2^+, H, H^+, O, O^+, Cu, Cu^+, Cu_2^+. We also use a similar set of particles for other mixtures. The results of calculations for water vapor plasma with impurities are shown in Figs.1-4.

It can be seen that the results of calculating the electrical conductivity of a water vapor plasma with copper impurities significantly depend on the e^-+Cu cross-section model. Thus, in the case of using the non-resonant scattering model [18] (relatively small cross-section value), we have a continuous increase in electrical conductivity with increasing temperature due to an increase in the electron concentration due to thermal ionization.

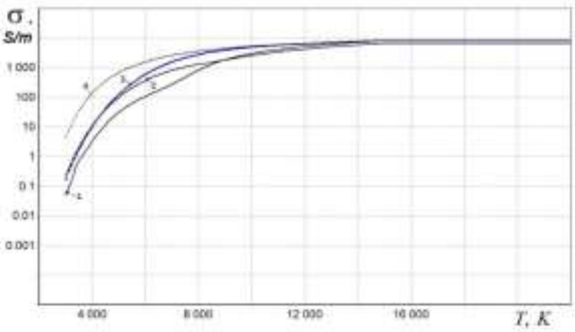

Fig. 1. Electrical conductivity of the plasma of a water-vapor for equimolar mixture containing copper (pressure p=10 bar). Curves 1 denotes pure water vapor; 2 is H_2O–Cu (90:10) (the resonant cross-section model e^-+Cu [17]), 3 is H_2O–Cu (90:10) (an alternative cross-section model e^-+Cu [19]); 4 is H_2O–Cu (90:10) (a non-resonant cross-section model e^-+Cu [18])

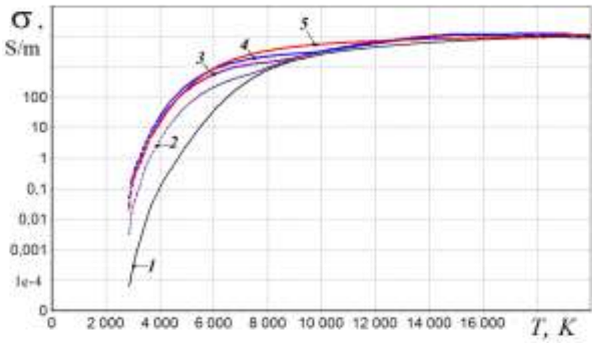

Fig. 2. Plasma conductivity of a water-vapor equimolar mixture containing iron (pressure p=10 bar). Curves 1 denotes pure water vapor; 2 is H_2O–Fe (99:1); 3 is H_2O–Fe (90:10); 4 is H_2O–Fe (70:30); 5- H_2O–Fe (50:50)

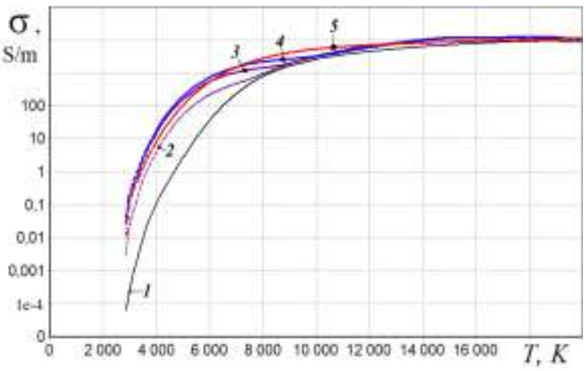

Fig. 3. Plasma conductivity of a water-vapor equimolar mixture containing iron and carbon (pressure p=10 bar). Curves 1 denotes pure water vapor; 2 is H_2O–Fe–C (99.9:0.5:0.5);3 is H_2O–Fe–C (95:2.5:2.5); 4 is H_2O–Fe–C (90:5:5); 5 is H_2O–Fe–C (70-20-10) (the mixture with the presence of clusters)

On the contrary, in the case of using the resonant scattering model [17] (relatively large cross-section value), the increase in electrical conductivity slows down and may even decrease due to an increase in the effective collision frequency due to the braking of electrons on copper atoms. In addition, we note that the use of an alternative cross-section model [19] gives an intermediate result between the specified cases. Therefore, there is a potential possibility of adding a sufficiently large amount of an impurity with certain properties to obtain a decrease in electrical conductivity in a multicomponent discharge plasma.

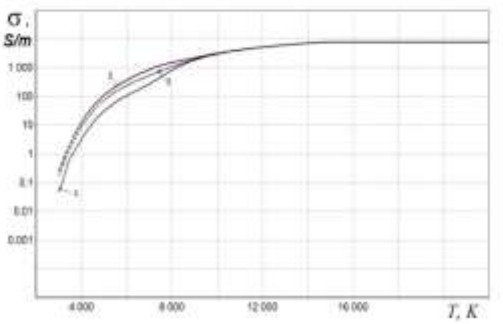

Fig. 4. Plasma conductivity of a water-vapor equimolar mixture containing tungsten (pressure p=10 bar). Curves 1 denotes pure water vapor; 2 is H_2O–W (90:10); 3 is H_2O–W (90:10) (the mixture with the presence of clusters)

The results of calculations for water vapor plasma with iron and carbon impurities are shown in Figs. 2, 3. With a similar plasma composition, we have results similar to the case of copper. However, it should be noted that carbon is characterized by the formation of clusters in the discharge plasma. The composition of the plasma due to the processes of association of carbon atoms into clusters $C+C_n=C_{(n+1)}$ are supplemented by particles that are larger in size than molecules and radicals of the water vapor medium. These can be simple clusters or complex formations (fullerenes), including those with metal inclusions. Accordingly, clusters have a larger scattering cross section for low-energy electrons, which causes a change in the integral characteristics of interparticle interactions in the plasma.

It should also be noted that for such a refractory metal as tungsten, the formation of clusters in the plasma is a characteristic feature. Taking into account the presence of clusters (n=2–36) gives a decrease in the electrical conductivity of the plasma (see Figs. 3, 4). Therefore, the presence of cluster in a multicomponent plasma can also be a factor into reducing the electrical conductivity.

MEASUREMENT OF ELECTRICAL CONDUCTIVITY OF PULSED DISCHARGE PLASMA

The influence of metal impurities on the properties of pulsed discharge plasma in water was experimentally investigated by initiating an electric explosion of a metal conductor when a high-density pulsed current was passed through it [20]. When using "thin" conductors with a diameter of up to 20 μm, the most intense lines in the plasma spectrum are hydrogen lines in the active phase of the discharge. With an increase in the diameter of the conductors, the lines of the conductor material become dominant in the radiation spectrum.

The specific electrical conductivity of a dense plasma of an electric discharge in water was determined based on the time-dependent changes in the plasma resistance and the radius of the discharge channel. The electrical conductivity was calculated by averaging several measurements of the resistance and the radius of the channel. The volume-averaged conductivity was calculated for a relatively large interelectrode distance (l = 40 mm). Volume averaging was performed taking into account the fact that the difference in brightness temperatures is insignificant along the channel axis and does not exceed the value of $(3…4)·10^3$ K, and radiative heat conduction and high collision frequency should lead to temperature equalization across the discharge channel cross section. This phenomenon is facilitated by the so-called "the slit effect" that occurs in dense non-ideal plasma [21-24].

In addition, there should be a redistribution of absorption energy in the spectra towards higher frequencies, which at temperatures $T=(10…50)·10^3$ K should lead to rapid temperature equalization across the channel cross section. Based on this, we will assume that the current is distributed almost uniformly across the discharge channel cross section with rapid energy input. Conductivity calculations will be performed for such regimes.

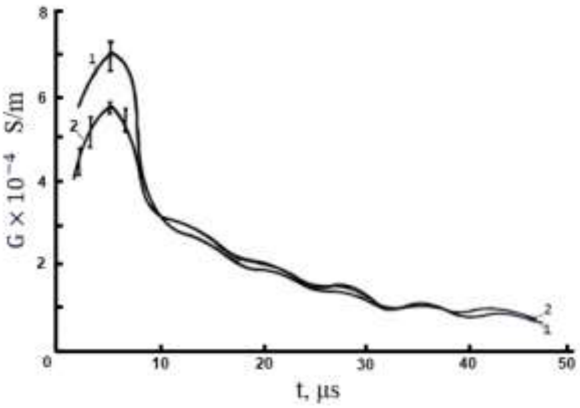

Fig. 5. Electrical conductivity of pulsed discharge plasma in water as a function of time and conductor material (U=37 kV, l=40 mm, L=0.43 μH). Curves 1 denotes W (d=160 μm); 2 is Cu (d=180 μm)

The results of calculations of the volume-averaged specific electrical conductivity of plasma channels depending on the discharge duration are shown in Figs. 5-7. It can be seen that the maximum value of electrical conductivity is observed in the first half-period of the discharge, when there is intensive energy input into the channel and plasma heating to tempe-?atures $T=(10…50)·10^3$ K. Over time, the electrical conductivity of the plasma decreases, which correlates with the behavior of the brightness temperature over time.

When studying the influence of copper and tungsten impurities on the properties of plasma initiated by an electric explosion of a conductor, conductors with a diameter of 160…180 μm were used. For a detailed study of the influence of tungsten impurities on electrical conductivity, conductors with a diameter of 20 to 500 μm were used. This corresponds to the number of metal atoms per unit length of the channel $N_a = 2\cdot10^{17}\ldots1.25\cdot10^{20}$ atom/cm. The interelectrode distance was l = 40 mm, the voltage U was chosen to be 20 and 37 kV. The discharge period was t = 15.5 μs with a capacitance C = (14.6 ± 0.2) μF and an inductance L = 0.43 μH of the discharge circuit. The current-voltage and space-time characteristics of the plasma channel were measured with reference to time.

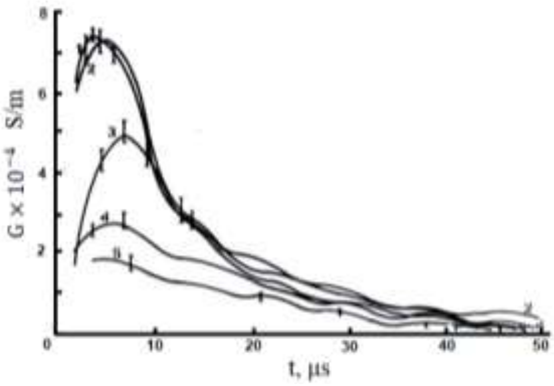

Fig. 6. Electrical conductivity of pulsed discharge plasma in water as a function of time for a tungsten conductor (U=20 kV, l=40 mm, L=0.43 μH). Curves 1 denotes W (d=20 μm), 2 is W (d=75 μm), 3 is W (d=160 μm), 4 is W (d=300 μm), 5 is W (d=500 μm)

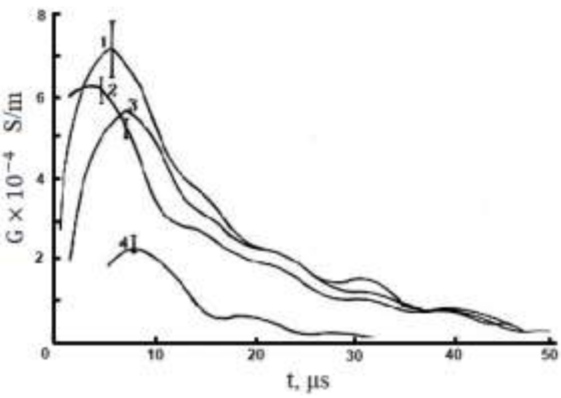

Fig. 7. Electrical conductivity of pulsed discharge plasma in water as a function of time and conductor material (U=37 kV, l=40 mm, L=0.43 μH). Curves 1 denotes W (d=160 μm), 2 is Fe (d=160 μm), 3 is Cu (d=180 μm), 4 is C (d=180 μm)

The results of calculations of the volume-averaged specific electrical conductivity of the discharge plasma show that the electrical conductivity depends both on the type of metal impurity (see Fig. 5) and on its amount in the discharge channel (see Fig. 6). At the same time, a change in the amount of energy input does not affect the overall dynamics of electrical conductivity depending on the concentration of metal impurities in the plasma (see Fig. 7). We note that this is true for a relatively large interelectrode distance l = 40 mm. When this distance decreases, the role of near-electrode processes increases. It is also possible to introduce additional impurities into the discharge channel through erosion and evaporation of the electrodes, as well as the appearance of cathodic and anodic jets.

Also from the presented results (see Figs. 5-7) it is clear that an increase in the concentration of certain impurities (tungsten or carbon) in the plasma of the discharge channel leads to a significant decrease in the value of electrical conductivity. At the same time, in the early stages of the discharge, the electrical conductivity is higher than in the later stages..

DISCUSSION

The calculations and experimental results show that metal impurities can significantly affect the electrical conductivity of the plasma of pulsed discharges in water compared to the discharge in an aqueous medium without impurities. After all, metals have a much lower ionization potential compared to water molecules, therefore, the introduction of metal impurities leads to an increase in the degree of plasma ionization. In dense plasma, due to thermal ionization, this leads to an increase in the number of charge carriers, and if there are no other significant factors, a typical picture is observed: the introduction of metal impurities increases the density and electrical conductivity of the plasma.

On the other hand, some impurities can reduce the electrical conductivity of the plasma. This may happen if the impurities have certain properties, in particular a large cross section for scattering low-energy electrons by atoms. Such properties are inherent only to individual elements. Therefore, a decrease in electrical conductivity when introducing impurities is occured only if the certain components are present in the mixture.

It should be noted that there are significant discrepancies in the values of the transport properties of multicomponent plasma of electric discharges containing copper, which are calculated using different models of the transport cross section of electron scattering on copper atoms. These discrepancies complicate the accurate modeling and prediction of the behavior of such plasma. Therefore, for a better understanding and agreement of the results, additional studies are needed that would take into account various factors and experimental conditions. In particular, the influence of the concentration of copper impurities, temperature conditions and other parameters on the electrical conductivity and other transport properties of the plasma should be studied in more detail. Therefore, the characteristics of plasma of electric discharges containing copper vapors require further study, which will allow developing more accurate models and improving our knowledge of this process.

The decrease in electrical conductivity can also be due to the presence of clusters in the plasma, which is a fairly common phenomenon for plasma media containing copper and tungsten [25-36]. Clusters are observed in both low-temperature and high-temperature plasma devices. Therefore, the effect of decreasing electrical conductivity can be used to change the properties of plasma over a wide temperature range.

It should also be noted that the properties of dense plasma can be affected by non-ideality effects, which are taken into account differently in different plasma models [21-25], which leads to divergent results depending on the plasma density. The approach used in this work [12, 14-16] in the limiting case of zero density reduces to the Spitzer formula for the plasma condu-?tivity [37, 38]. In addition, there are certain features depending on the type and geometry of the discharge.

Therefore, the electrical conductivity of the plasma of pulsed discharges in water can be both increased and decreased by introducing the certain impurities. This opens up possibilities for targeted control of the properties of such discharges.

CONCLUSIONS

The presented results of the study show that even small amounts of impurities can significantly change the electrical conductivity coefficient of pulsed discharge plasma compared to a discharge in an aqueous medium without impurities. The value of electrical conductivity in multicomponent plasmas containing impurities largely depend on the value of electron scattering cross section on atoms, which determine the efficiency of the interaction of electrons with impurity atoms.

The plasma-water vapor medium containing clusters has significantly different properties from that of a medium without impurities. Thus, impurities can both increase and decrease the electrical conductivity of the plasma, depending on their characteristics and concentration. This opens up opportunities for targeted control of plasma properties, which can be used in various application areas.

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ПРО ОСОБЛИВОСТІ ВПЛИВУ ДОМІШОК МАТЕРІАЛУ ЕЛЕКТРОДІВ НА ЕЛЕКТРОПРОВІДНІСТЬ ПЛАЗМИ ІМПУЛЬСНИХ ЕЛЕКТРИЧНИХ РОЗРЯДІВ У ВОДІ

В.В. Гладковський, В.Г. Панченко, П.В. Порицький, О.А. Федорович, Л.М. Войтенко, Л.М. Свята

Розглянуто вплив домішок матеріалу електродів на електропровідність плазми імпульсних розрядів у воді. Проведено експериментальні дослідження електропровідності та виконано розрахунки, що ґрунтувалися на методі моментів Ґреда. Показано, що невелика кількість домішок металів та вуглецю може суттєво змінити величину коефіцієнта електропровідності плазми порівняно із випадком чистої водяної пари. Виявлено, що домішки металів та вуглецю можуть спричиняти як збільшення, так і зменшення електропровідності плазми, що пов’язано із процесами міжчастинкових зіткнень та наявністю кластерів.