ON PECULIARITIES OF THE RADIAL TEMPERATURE DISTRIBUTION IN A CHANNEL OF PULSED DISCHARGE IN WATER AT THE RELAXATION STAGE

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The results of measurements of the radial temperature distribution of pulsed discharges in water are reported. The data obtained concern the relaxation stage for discharges with small inductances of the discharge circuit and the active stage for discharges characteristic of pulsed discharge installations. A number of corrections, which are typical of the radiation emission of non-homogeneous, optically thick plasmas and take into account the features of the radiation output from a cylindrical plasma channel located in a liquid, have been made. The measurements of the maximal temperature along the observation beam path were carried out by analyzing the radiation intensity maxima of the reabsorbed hydrogen line H_α (656.3 nm) in both red and violet wavelength ranges. A practically plateau-like distribution of temperatures across the channel diameter has been obtained, which may be considered as an evidence for an almost uniform distribution of plasma parameters over the channel cross-section.

1. Introduction

Nonperfect plasma (NP) becomes more and more applicable in engineering projects, and its application in the future is promising. However, studying the most important plasma properties and revealing both relationships between them and their dependences on the key plasma parameters are not enough for constructing the reliable plasma models. For this purpose, it is also of importance to carry out fundamental researches of NP under extreme conditions. In the nature, NP constitutes a superdense medium of white dwarfs, the Sun, deep layers of giant planets in the Solar system and cosmophysical objects, where their structure and evolution are governed by the plasma properties [1]. Under laboratory conditions, NP can be created, as a rule, at explosions, powerful electric discharges in water and compressed gases, interaction of shock waves with gases, nuclear explosions, interaction between powerful laser radiation and a deuterium–tritium target in order to obtain a controlled thermonuclear synthesis, and so on.

As a rule, NP exists within very short periods (from a few microseconds to a few milliseconds). The appearance of NP is accompanied by the emergence of high and ultrahigh pressures and high temperatures; and this circumstance predetermines the difficulties, with which one is faced in the course of NP generation and its following researches.

Pulsed discharges in water (PDW) also give rise to the emergence of NP. Therefore, taking into account those ample opportunities which are proposed by the application of PDW plasma in technical products, the study of PDW is a challenging task. No model of a PDW channel has been developed yet. This demands that the detailed researches must be carried out concerning plasma parameters, their radial distributions, and their relationships with the key properties of hydrogen-oxygen NP that is formed at powerful electric discharges in water. This work aims at researching the radial distribution of temperature in PDW plasma at the relaxation stage, as well as in discharges typical of pulsed discharge installations.

2. Experimental Part, Results, and Their Discussion

At the initial discharge stage, the plasma of powerful PDW is optically opaque, and its optical thickness in the continuous spectral range can amount to tens or even hundreds of units. Under such conditions, the radiation emission produced by central regions cannot reach the surface, so that what is registered is radiated within a depth of no more than four mean free paths of quanta. At the late discharge stages, as the plasma relaxes, the pressure drops, the temperature decreases, the continuous spectrum intensity becomes reduced, and, accordingly, the optical thickness of plasma decreases as well. The plasma channel becomes transparent in the continuous spectral range; nevertheless, in lines – especially in the most intensive hydrogen line H_a

(656.3 nm) – the optical thickness still remains large, and this line becomes reabsorbed. At the stage of discharge relaxation, it becomes possible to register the reabsorbed line radiation emission of the channel and its distribution along the image radius.

We carried out the researches of the spatially and temporarily resolved spectra of radiation emission from the plasma channel. The measuring technique for such spectra is expounded in work [2]. The spectra were recorded with the help of a modified camera of a VFU-1 high-speed cinespectrograph; afterwards, the film was calibrated by intensity.

At the plasma relaxation stages, as well as at discharges typical of pulsed discharge installations, a line spectrum has been observed for some time; this spectrum contains the reabsorbed lines of hydrogen radiation emission belonging to the Balmer series H_α (656.3 nm) and the lines of metals belonging to the initiating conductor and the electrodes. In Fig. 1, the characteristic photoscans of the spatially and temporarily resolved spectra in the range 625–700 nm are depicted. The photoscans testify that, even in 50 μs after the relaxation stage having started (under given discharge conditions, energy had been supplied to the plasma channel during no more than 45 μs), the strong enough radiation emission in the continuous spectral range still remained (Fig. 1,a), and it was only in 70 μs that the reabsorbed line spectrum became observed (Fig. 1,b). At the same time, as is seen from panel b, besides the reabsorbed line H_α, the reabsorbed broadened lines of metals were also observed; the latter lines belong mainly to copper, the vapor of which is emanated from the electrodes. Therefore, in what follows, we used discharges in a 100-mm discharge gap for measurements; only the middle section of this interval was registered, which excluded the influence of metal admixtures on the measurement results, because they could not run over such a distance from the copper electrodes.

Measurements of the intensity I at the radiation maxima of reabsorbed lines make it possible to calculate the maximal – along the observation beam path – temperature by the Bartels' method [3,4]. All necessary conditions for this method to be eligible are fulfilled in RDW plasma: the plasma channel has cylindrical symmetry, plasma stays in the local thermodynamic equilibrium (LTE) [3, 4], and the temperature drops monotonically along the channel radius, which has been demonstrated experimentally in this work. As was shown in works [3,4], the decrease of the temperature can follow an arbitrary monotonic law. Film calibration was carried out in a wide range of intensity variation (by a factor of about 100) with the help of an EV-45 standard light source [5] and a specially developed 10-step attenuator with known attenuation factors for all steps and a known dependence of its transmittance on the wavelength. The fulfillment of the Bartels conditions and the calibration made allowed the distribution of the intensity of radiation emission of the reabsorbed hydrogen line H_α (656.3 nm) along the channel image radius to be measured. The treatment of photoscans and the intensity measurements were carried out by the method of homochromatic photometric measurements, the accuracy of which amounts to 10–12% [6].

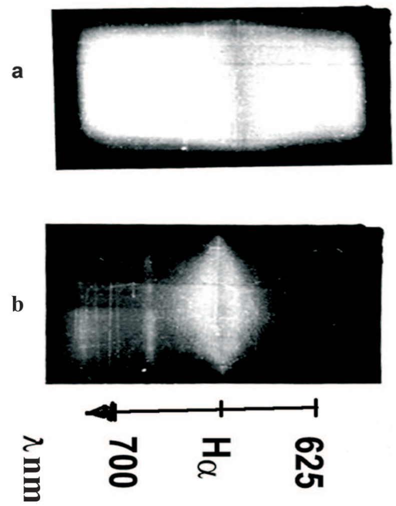

Fig. 1. Spatially resolved spectrograms of the PDW radiation emission in the spectral range 625–700 nm in 50 (a) and 70 μs (b) after the discharge relaxation stage started. U = 20 kV, $l = 40$ mm, $L = 0.43$ μH, and $W = 20$ μm

While measuring the intensity of the hydrogen line H_α (656.3 nm) in PDW and carrying out the calibration procedure, an EV-45 standard light source with a discharge in a capillary 2 mm in diameter and 10 mm in length, with fluoroplastic walls was used. The application of capillaries with fluoroplastic walls did not induce errors, because the discharge radiation spectrum of Teflon in this range is continuous and does not contain lines. Making use of capillaries with walls fabricated of polymethylmethacrylate or glass fiber laminate gave rise to the appearance of the reabsorbed line H_α in the reference source spectra, which made the intensity measurements in this spectral range incorrect [5].

In Fig. 2, the intensities of the hydrogen spectral line H_α in the channel image obtained at various distances from the channel axis are exhibited. The intensity measurements were carried out both in the red and

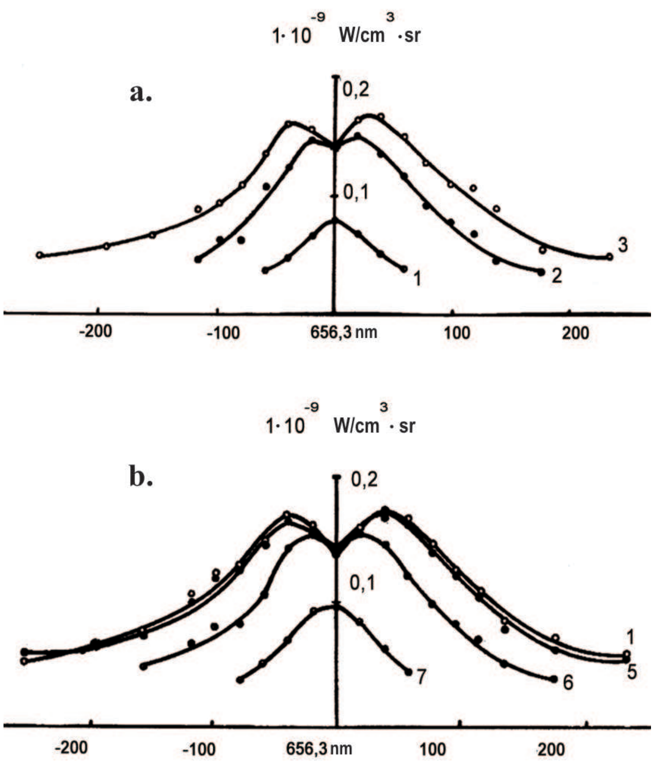

Fig. 2. Intensity distributions of the hydrogen spectral line H_α (656.3 nm) at various distances from the channel axis. $t = 76$ μs, $W = 20$ μm, $l = 100$ mm, $U = 30$ kV, and $L = 0.43$ μH

violet tails of the H_α line. The maximal values of the "temperature", obtained from the measured intensities in the radiation maxima of both tails, differed by 200–300 °C from each other, which did not exceed the measurement accuracy. Therefore, while correcting the intensity value, we used its average values and calculated the temperature maximal along the observation beam path by averaging two measurement values.

However, for the recalculation of the temperature distribution along the channel radius, it is necessary to introduce a number of correction coefficients, which would make allowance for the plasma inhomogeneity, the influence of optical thickness on the radiation emission intensity of H_α line, and the influence of peculiarities of the radiation output from the plasma channel in water on the radiation intensity. Let us consider those corrections in more details.

For an absolutely black body, the dependence of the radiation emission intensity on the temperature is determined by the Planck formula [4]

$$I(\lambda, T) = C_1 \lambda^{-5} (\exp(h\nu/kT) - 1)^{-1}. \tag{1}$$

In the case of inhomogeneous optically thick plasma, where the influence of a plasma channel inhomogeneity and the optical thickness on the line intensity I is to be taken into account, the Planck formula transforms into the following one [3, 4]:

$$I_\lambda = C_1 \lambda^{-5} \frac{MY[\tau(\nu), P]}{\exp(h\nu/kT_m) - M}, \tag{2}$$

where M is the parameter of inhomogeneity, Y is a function that takes the influence of optical thickness on the line intensity into consideration, and T_m is the temperature maximal along the observation beam path. This formula takes the stimulated radiation emission into account as well, because its neglecting at $T = 16 \times 10^3$ K would bring about an error of 4×10^3 K directed towards the temperature overestimation.

Taking into account that the broadening of H_α line has a Stark origin, let us determine the correction coefficients M and Y. The conditions of eligible applicability of the relations for M and Y to the H_α line in the case of PDW plasma are obeyed with safety [3, 4]:

$$\frac{kT_m}{E_n + 1/2E_0} < 0.3.$$

At the stage of plasma decay, $T_m < 2 \times 10^4$ K, the potential of lower level excitation $E_n = 10.2$ eV, and the potential of hydrogen atom ionization $E_0 = 13.6$ eV. Hence, we obtain

$$\frac{2 \text{ eV}}{(10.2 + 6.8) \text{ eV} \leq 0.12}.$$

For the case of Stark broadening, the parameter of inhomogeneity for the H_α (656.3 nm) line was calculated by the formula [3, 4]

$$M = \sqrt{\frac{E_n + (1/2)E_0}{E_m + (1/2)E_0}} = \sqrt{\frac{10.2 + 6.8}{12.09 + 6.8}} = 0.95, \tag{3}$$

where $E_m = 12.09$ eV is the potential of top level excitation. In the same approximation, the parameter P can be calculated by the formula [3, 4]

$$P = \frac{6}{\pi} \text{arctg} \frac{M^2}{\sqrt{1 + 2M^2}} = \frac{6}{\pi} \text{arctg} \frac{0.95^2}{\sqrt{1 + 2 \cdot 0.95^2}} = 0.97, \tag{4}$$

and the value obtained can be used to determine $Y(\tau)$ from the dependence $Y(\tau) = f(M, P)$ [3, 4]. The value of T_m can be determined for any reabsorbed line, but

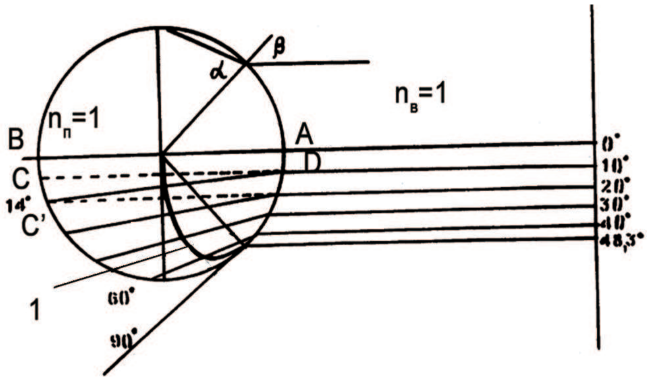

Fig. 3. Transformation of the discharge-in-water channel into its image on a film. Curve *1* corresponds to the displacement of the channel radius on the channel image (the middle-points of chords of those beams which quit the channel in parallel at different distances from the channel axis)

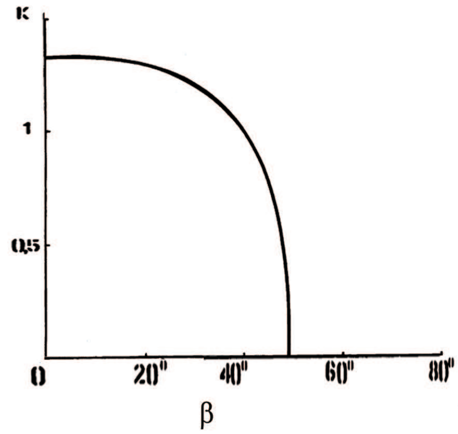

Fig. 4. Dependence of the correction coefficient for recalculating the channel image intensity on the output angle of radiation emission (see Fig. 3)

a resonance one. For the H_α line, we have $\tau_m = 4$ and $Y = 0.97$. The latter quantity is a correction for the influence of optical thickness on the radiation emission intensity I at the maximum.

Above, we have analyzed the general corrections for inhomogeneous optically thick plasma. Now, let us consider the corrections that are specific of cylindrical discharges in liquids. The first one is the correction for a change of the channel dimensions at the projection of the latter onto a film. It stems from the fact that, while radiation quits the channel, the inclination angle of the beam changes at the plasma–water interface following the law $\frac{\sin\alpha}{\sin\beta} \approx \frac{n_1}{n_2}$, where α and β are the incidence and output angles of the beam, respectively ($\alpha = 0 \div 90°$, $\beta = 0 \div 48.3°$); and n_1 and n_2 are the refractive indices of water and plasma, respectively. In Fig. 3, the process of channel transformation into the projection of its image onto a film is illustrated.

The limiting value for the output angles of those beams, which move in parallel in water (and, correspondingly, enter the objective), amounts to 48.3°. In the first approximation, the refraction of beams, which occurs owing to the presence of the pressure gradient in water and, accordingly, to a change of the refraction coefficient n, is not taken into account. However, as was shown above, the magnitude of n-variation is insignificant and, therefore, can be neglected. The visible, on the film, radius of the channel in the self-luminous state is equal to 0.746 ($\sin\beta = \frac{1}{n} = \frac{1}{1.34} = 0.746$ at $\beta = 48.3°$) times the actual radius (diameter) of the channel; the latter can be obtained at the shadow filming of the channel with its illumination by an external light source. In our case, for the lighting of the channel, we used an EV-45 standard source with a capillary 2 mm in diameter installed at the focus of a lens 170 mm in diameter with a focal length of 200 mm; the temperature in the capillary was 40×10^3 K. In such a way, a parallel intensive lighting beam for photographing the shape and the actual dimensions of the plasma channel was obtained [8]. It is clear that, while measuring the T-distribution along the channel radius, this transformation must be taken into account; moreover, together with the transformation of channel dimensions themselves, the correction for the intensity value has to be included as well. The latter can be determined from Fig. 3.

Provided that the plasma in the channel is transparent, the registering film gets light more by the same factor as the area of sector ABC′D is larger than the area of sector ABCD, *etc.* This circumstance originates from the fact that the light refraction at the plasma–water interface allows light from a larger volume, which is proportional to the increment of the sector area, to illuminate a unit area of the film. There is no such transformation along the channel, provided that the observation is carried out in the direction perpendicular to the channel. Therefore, in the case of cylindrical symmetry, only the ratio between the indicated areas must be taken into account.

The results of calculations, which were made for the dependence of the correction coefficient on the output angle following the procedure described in work [9], are shown in Fig. 4. The values of the coefficient K demonstrate how much the intensity of the channel image is higher than the intensity of the channel itself,

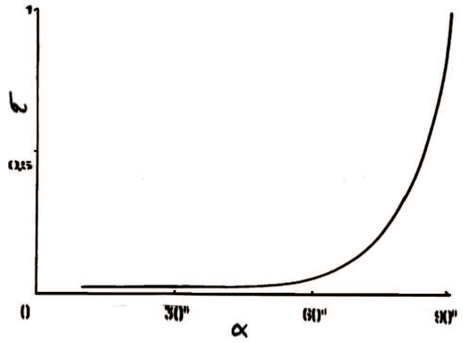

Fig. 5. Dependence of the reflection coefficient for a plasma–water interface on the beam incidence angle

and the dependence of their ratio on the angle between the radiation output direction and the discharge axis. The intensity amplitude obtained at the image should be divided by this coefficient. The latter changes from 1.34 in the central part of the channel (the output angle is below 15°) down to 0.74 at 45° and 0 at 48.3°.

A third correction ρ is associated with the necessity to make allowance for the dependence of the coefficient of reflection from the plasma–water interface on the incidence angle of the beam quitting the plasma. If the pressure changes from 100 to 1000 atm, the refractive index of water varies from 1.335 to 1.35 (the index of refraction of non-compressed water $n_0 = 1.33$). For the sake of simplicity, let n be constant and equal to 1.34. The limiting angle of the beam output from plasma into water satisfies the relation $\sin\alpha = \frac{1}{n} = 0.746$, so that $\alpha = 48.3°$. The corresponding correction ρ is determined by the Fresnel formula [7]

$$\rho = \frac{1}{2}\left[\frac{\sin^2(\alpha-\beta)}{\sin^2(\alpha+\beta)} + \frac{\mathrm{tg}^2(\alpha-\beta)}{\mathrm{tg}^2(\alpha+\beta)}\right], \qquad (5)$$

where α and β are the incidence and refraction angles, respectively, and $\sin\alpha/\sin\beta = n$, because $n_{\rm pl} \approx 1$.

The results of calculations are exhibited in Fig. 5. One can see that this coefficient changes from 2% at the normal incidence of the beam onto the plasma–water interface to unity (which means the total reflection) at an incidence angle of 90°. Therefore, the correction is essential at the incidence angle larger than 60°, which leads to the increase of the actual temperature in the plasma channel near its boundaries: the closer we are to the boundary, the higher is the temperature.

The non-corrected and corrected results of measurements of the radial temperature distribution in the pulse discharge channel at the relaxation stage, provided that the inductance of the discharge is low ($L = 0.43\ \mu$H),

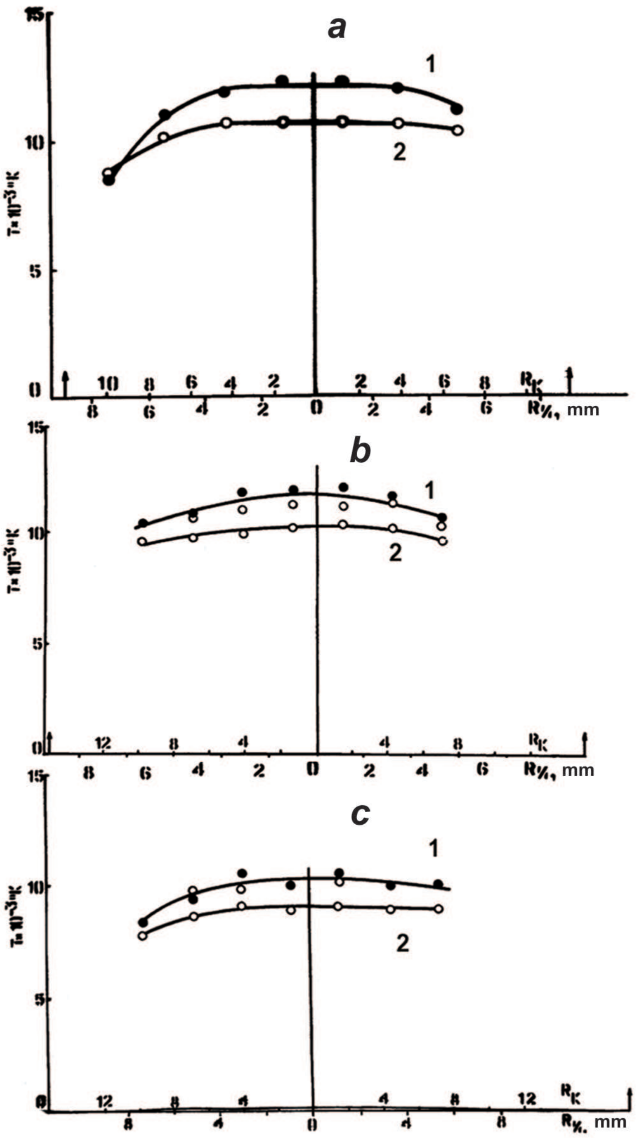

Fig. 6. Radial distributions of the maximal – along the observation beam path – temperature in the channel before (*1*) and after (*2*) correction. The relevant parameters are: (*a*) $t = 77\ \mu$s, $L = 0.43\ \mu$H, $l = 100$ mm, $U = 30$ kV; (*b*) $t = 175\ \mu$s, $L = 22.2\ \mu$H, $l = 100$ mm, $U = 30$ kV; and (*c*) $t = 240\ \mu$s, $L = 22.2\ \mu$H, $l = 100$ mm, $U = 30$ kV

and at the active stage of discharges typical of pulsed discharge installations are given in Figs. 6,*a* and *b*. The parameters of the installation and discharges were as follows: the capacity of the capacitor bank was 14.5 μF, the inductance of discharge circuit $L = 0.43\ \mu$H and $L_1 = 110\ \mu$H, the initial voltage across the capacitor bank $U_0 = 30$ kV, and the length of discharge gap

$l = 100$ mm. For the sake of good reproducibility of results, the discharge was triggered with the help of an initiating tungsten wire 20 μm in diameter (with a minimal amount of metal admixtures in the channel).

In Figs. 6,*a* and *b*, the arrows denote the channel boundary positions. The numbers over the horizontal axis (the radius axis) mean the radius of the channel, the numbers under the axis give the radius of its image. Curves *1* correspond to the radial distributions of the maximal – along the observation beam path – temperature in the case where no correction is made for the cylindrical shape of the channel and the image transformation, whereas curves *2* correspond to the corrected distributions of T_m, with all above-mentioned corrections being taken into account. In comparison with the non-corrected temperature T, the actual one turns out to be reduced in the central part of the channel and elevated at its boundaries. The temperature distribution across the channel is almost plateau-like (Fig. 6) with an insignificant reduction towards the channel boundaries. Such a distribution observed at the relaxation stage of fast discharges ($L = 0.43$ μH) and at the active stage of discharges typical of pulsed discharge installations enables one to assume that the PDW plasma channel is practically uniform. This circumstance considerably simplifies the calculations of the channel conductivity and the current distribution in the channel and allows the correct plasma models to be constructed. Only an insignificant reduction of the temperature at the channel boundaries is observed, which is associated with the radiation emission through the plasma–water interface. The equalizing of the temperature over the channel cross-section testifies to a high efficiency of the radiant heat conductivity in a dense nonperfect plasma, which can be connected with the increase of the quantum path length in NP. Such an increase can be due to the NP enlightenment effect [10], which, in its turn, occurs owing to the cutoff of top atomic levels in microfields and the reduction of free electron capture onto orbits inherent to free atoms (ions).

3. Conclusions

A new technique for measuring the radial distribution of temperature in pulse discharges in water at the relaxation stage and in discharges characteristic of pulsed discharge installations has been developed, and its approbation has been carried out. A number of corrections originated from both the features of the radiation emission from the inhomogeneous optically thick plasma and the features of the radiation output from the cylindrical plasma channel into water have been taken into account. The temperature maximal along the observation beam path was evaluated according to the measured intensities in the maxima of radiation emission in the red and violet tails of the reabsorbed hydrogen line H_α (656.3 nm) of the Balmer series. An almost plateau-like distribution of the temperature along the channel radius has been obtained for a powerful PDW at its relaxation stage and for the active stage of discharges typical of pulsed discharge installations. It allows the model of practically uniform distributions of the temperature and other parameters across the PDW channel to be applied. An insignificant reduction of the temperature was observed only near the channel boundaries, which is associated with radiation emission from the channel.

1. V.E. Fortov and I.T. Yakubov, *Physics of Nonideal Plasmas* (Hemisphere, New York, 1989).
2. L.L. Pasechnik, P.D. Starchik, and O.A. Fedorovich, in *Theory, Experiment, and Practice of Pulsed Discharge Technology* (Naukova Dumka, Kyiv, 1987) (in Russian), p. 14.
3. G. Bartels, Izv. Akad. Nauk SSSR, Ser. Fiz. **22**, 742 (1958).
4. W. Lochte-Holtgreven, *Plasma Diagnostics* (North-Holland, Amsterdam, 1968).
5. A.N. Demidov, N.N. Ogurtsova, and I.V. Podmoshensky, Optiko-Mekhan. Promyshl. N 1, 2 (1960).
6. V.I. Malyshev, *Introduction to Experimental Spectroscopy* (Nauka, Moscow, 1979) (in Russian).
7. M.I. Apenko and A.S. Dubovik, *Applied Optics* (Nauka, Moscow, 1971) (in Russian).
8. V.L. Budovich, A.S. Bizyaev, I.P. Kuzhekin, and O.A.Fedorovich, Teplofiz. Vysok. Temp. **21**, 544 (1989).
9. M.Ya. Vygodskii, *Handbook on Elementary Mathematics* (Nauka, Moscow,.1973) (in Russian).
10. A.Yu. Popov and O.A. Fedorovich, in *Abstracts of the 4-th Conference on Electric Discharge in Liquid and Its Industrial Application (Nikolaev, 1988)* (in Russian), part 1, p. 13.

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ПРО ОСОБЛИВОСТІ РАДІАЛЬНОГО РОЗПОДІЛУ ТЕМПЕРАТУРИ В КАНАЛІ ІМПУЛЬСНИХ РОЗРЯДІВ У ВОДІ НА СТАДІЇ РЕЛАКСАЦІЇ

О.А. Федорович

Р е з ю м е

Наведено результати вимірювань радіальних розподілів температури імпульсних розрядів у воді на стадії релаксації розрядів з малими індуктивностями контура та на активній стадії розрядів, характерних для розрядно-імпульсних установок.

Введено ряд поправок, які характерні для випромінювання неоднорідних оптично товстих плазм і які враховують особливості виходу випромінювання з циліндрічного плазмового каналу, котрий знаходиться у рідині. Вимірювання максимальної вздовж променя спостереження температури проводилось за інтенсивністю випромінювання в максимумах випромінювання реабсорбованої лінії водню H_α (656,3 нм) як в червоному, так і в фіолетовому крилі. Одержано практично платоподібний розподіл температури по діаметру каналу, що можна вважати свідченням майже рівномірного розподілу параметрів плазми по перерізу каналу.