ON FEATURES OF THE RADIATION FROM PULSED DISCHARGES INITIATED BY THICK WIRES IN WATER

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The investigation results on the distribution of the plasma channel radiance intensity in the visible spectral region are reported. The pulsed discharge in water is initiated by the Tungsten wire (Ø 300 μm) explosion under initial battery voltage of 20 kV. The plasma channel radiance intensity does not correlate with the power contribution into the plasma. The energy contribution ceases at 20 μs, and the maximum radiation of the continuous spectrum is observed at 80 μs. The radiation intensity is practically constant between 50 and 120 μs. “Unrealization” of tungsten linear spectrum levels takes place up to the basic state. It is not succeeded to record the intensity ($T_n \leq 6\ 10^3$ K) in the interval to 20 μs. The dynamics in time of the absorption line spectrum in the region between 490…560 nm, explaining the radiation intensity increase with time, is investigated. The visible radiation region comprises a wave length band corresponding to the plasma frequency in the channel. In the course of time, the plasma frequency band displaces into the red spectral region and the radiation intensity in the violet region increases to the values corresponding to $T = 2\ 10^4$ K. The radiation reflection from the channel boundary at the plasma frequency takes place. The time dependence of the pressure obtained from the experimental hydrodynamic calculation results has been compared with the adiabatic curve. A significant difference between results is evident. The same calculation for the temperature change shows that at the initial discharge stage $T = 3\ 10^4$ K should be reached. The radiation spectrum dynamics in the region between 620 and 700 nm is shown. In the H_α line region (656.3 nm) neither the absorption line nor the radiation line are observed in the spectrum up to 83 μm.

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INTRODUCTION

The only source of information about the temperature and concentration of the dense plasma is its radiation. But these plasma parameters can be determined from the distributions of intensities and their absolute values observed in the visible radiation region. The literature practically has no data in this field, in particular, at electron concentrations exceeding $N_e \geq 10^{19}$ cm^{-3}. It is explained by a lack of methods for determining the intensities in this part of the spectrum and their distributions in the broad spectral region in the case of fast processes with the time resolution of ≤ 1 μs. Our aim is to investigate the radiation spectra in the visible range of the plasma channel of pulsed discharges (PDW) in water initiated by tungsten wires of 300 μm in diameter, and to study the correlation of radiation intensities (radiance temperature) in relation with the power contribution into the plasma channel.

LITERATURE REVIEW

Papers [1-15] present the results on the radiance temperature of the plasma channel of pulsed discharges in water. The results reported are very different because the measurements have been carried out with various rates of energy input into the channel. Besides the discharges were initiated using the wires of different materials and different diameter. Probably, purely spark discharges were investigated. However, the authors of the above-mentioned papers practically do not consider the problems of the time evolution of radiation- and absorption spectra. Also, the spectral distributions of the plasma radiation in the visible part of the spectra are not investigated. In [1] only the initial stage of the discharge is investigated. An enough strong nonequilibrium of the continuous radiation spectrum in the visible spectral region is observed. Analysis of divergence of results in [1, 2, 4] shows that they have been obtained for very different discharge conditions. The damping periods, lengths of discharge gaps, energies contributed into the channel, diameters and materials of initiating wires, initial voltages and so on were different. Only in several papers the radiance temperature was measured in the narrow spectral region [3, 4, 6] and, solely, for the first current half-period. The results of absolute measurements of spectral PDW distributions in the literature are not presented. That is the reason of the interest to the study of spectral distributions of the PDW plasma channel radiation for the calculation of the energy balance in the channel too. Papers [11-14] give the radiation intensity distributions in the visible spectral regions in fixed instants of time. Paper [15] also reports the measurement results on the relative distribution of the radiation spectrum in the visible region for the case of copper wire explosion in water in fixed instant of time.

As noted above, the measurement results are very different as investigations were carried under diverse conditions.

EXPERIMENTAL RESULTS

The source of the plasma is a pulsed discharge in water initiated by the tungsten exploding wire of 160…500 μm. A low-inductance capacitors battery was used as a generator for dense plasma production. Its capacity was 14.6 μΦ, discharge period 15.5 μs, capacitor voltage 7.5…37 kV. The most interesting were operating conditions with initiation of discharges by the tungsten wire of 320 μm under battery voltage of 20 kV. The oscillogram of the current and voltage drop in the discharge gap of 40 mm in length is given in

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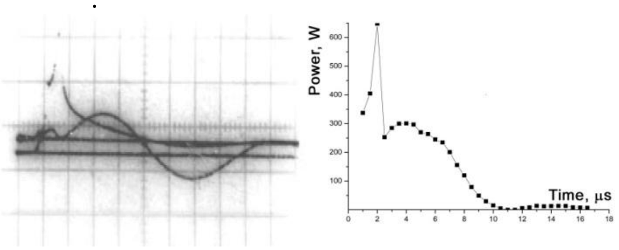
Fig. 1,a,b shows the power contribution into the discharge. One can see from the figure that the main energy contribution into the discharge occurs in the first half-period, i.e. during the first 10 μs.



a *b*

Fig. 1. a – Oscillogram of the current and voltage drop in the discharge gap, U_0 = 20kV, discharge gap length is 40 mm, Tungsten, 320 μm; b – Time dependence of the power released in the discharge gap (the same conditions)

In the second and subsequent half-periods the energy contribution into the channel is insignificant and does not exceed 10% of the energy accumulated in the battery. Consequently, there occurs a classic damping of the plasma channel expanding in water. The time characteristics of the radiance intensity of the discharge plasma, as well as, of the radiation and absorption spectra resolved in the visible region were investigated. The experimental techniques are described in [3, 7].

The intensity of spectra was calibrated using a standard source EV-45 [16] and special nine- or ten-step attenuators with measured transmission coefficients. For measurements of low intensities additionally a gray filter was used and double film calibration by means of nine-step attenuators was performed.

Fig. 2 presents the time dependence of the radiance temperature measured by the radiation intensity of the plasma channel. The discharge was initiated by the explosion of Tungsten wires. Measurements were carried out on the wave length of 475.0 nm in the spectral region free of Tungsten radiation (absorption) line. The spectral region was chosen with the aid of a narrow-band interferential light filter. Pictures were taken using a camera VFU-1 with the time resolution of 0.5 μs and the treatment was performed in 2 μs. In the time characteristic curve of the radiation intensity of the plasma channel initiated by the W wire (Ø 150 μm and more) a rather paradoxical radiation effect is observed (Fig. 3). At the instant of maximum energy supply into the channel the plasma practically does not radiate and it is impossible to determine the radiance temperature. At the initial discharge stage (2…3 μs) the tungsten wire vapor heating to (8…9)· K is observed. After the breakdown and intense energy supply into the plasma channel, it ceases to irradiate.

Across the plasma channel surface the bright and dark spots, so-called, striations, were observed. However, at once the glow was not observed even in the bright plasma regions. After a time the bright channel region intensity was measured. The duration of the radiation “pause” is changing but equals to 20 μm in the case of the discharge initiating wire (DIW) diameter of 150…500 μm. The duration of the glow “pause” increases with wire diameter increasing while the initial battery voltage is constant. The radiation intensity changes in the dark and light regions of the plasma channel are shown in Fig. 2. It is seen that for the DIW diameter of 300 μm (U_0=20 kV) the difference in the radiance temperature values is not more than ±1 10^3 K. At the similar wire diameter and the voltage U_0 = 30 kV the temperature spread ΔT from the average T is ±2 10^3 K and decreases with time.

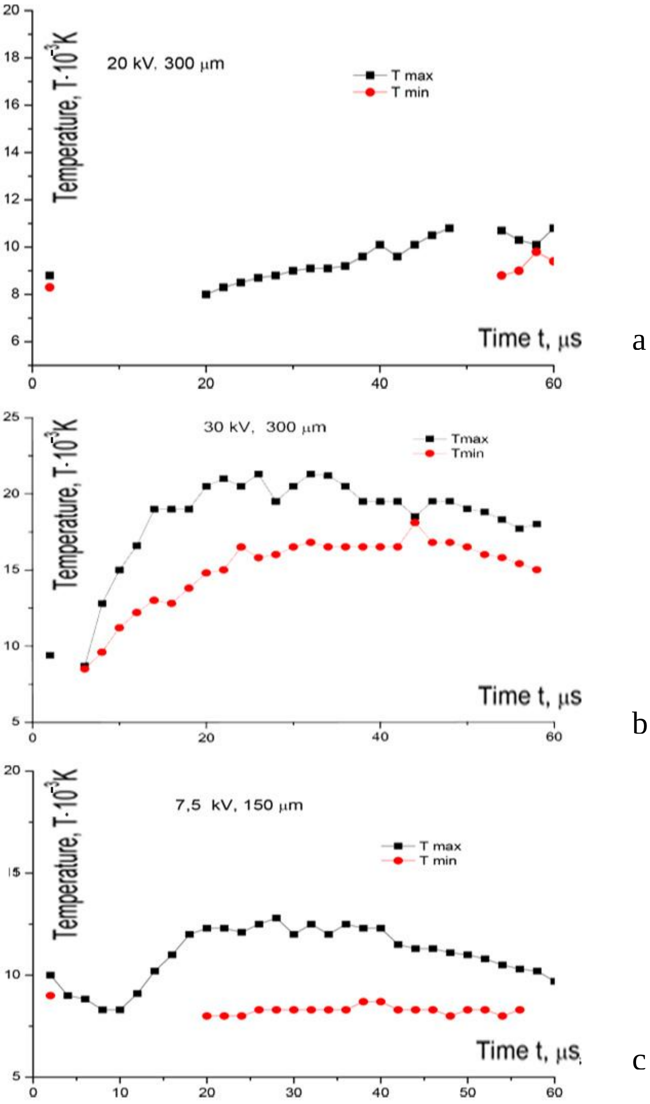


Fig. 2. Time dependence of the plasma channel radiance temperature for three discharge modes; a – Tungsten, 300 μm, 20 kV, 40 mm; b – Tungsten, 300 μm, 30 kV 40 mm; c – Tungsten, 150 μm, 7.5 kV 40 mm

It should be noted a one more radiation feature when the thick wires are used, i.e. the larger diameter of the discharge initiating wire, the longer the radiation existence in the later discharge stages. Let us consider the dynamics of radiation intensity distribution in the visible spectral range for the radiation of the plasma being formed as a result of the wire explosion in liquid. Fig. 4 shows the radiation distribution immediately in 3 μs after the breakdown. In the radiation distribution a continuous spectrum with the faint hydrogen lines H_α and H_β of Balmer series are seen.

In the radiation the hydrogen lines are observed, and their width is not very broad. This indicates on the comparatively low electron concentration N_e – not higher than $5\ 10^{18}$ cm^{-3}. The radiation distribution in the continuous spectrum is similar to the radiation of the absolute black body (BB) and corresponds approximately to the BB temperature $7\ 10^3$ K. As N_e increases the hydrogen lines become still broader and disappear from the spectrum.

Despite the intensive energy contribution into the channel in 10 µs, the plasma almost ceases to radiate in the visible range and radiates only in the region of the line H_α (see Fig. 3,a). At 23 µs the radiation intensity increases in the red region and its radiance corresponds to the radiance temperature of $11\ 10^3$ K, while in the violet spectral region the radiance temperature does not exceed $6\ 10^3$ K. At the same time, in the absorption spectra the broadened absorption lines appear. They belong to the lines of the transition to the lowest level of tungsten (transition from the primary level to the first level), see Fig. 3,b. However, at this time the absorption line in the region of the line H_α (656.3 nm) is not observed throughout the region of the plasma channel glow (see Figs. 3,a-h).

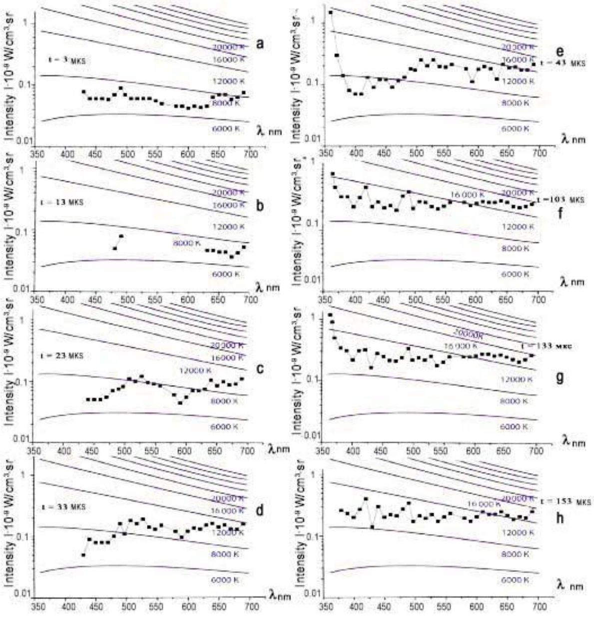


Fig. 3. Radiation distribution in different instants of time

At 43 µs the most considerable discrepancy of the radiance temperatures is observed in the different spectral regions - from $20\ 10^3$ K in the violet spectral region (where 10 µs before it was not succeeded to record the radiation) to $7\ 10^3$ K in 400 nm wavelength region, and the increase up to $16\ 10^3$ K – in the red spectral region.

In this distribution the visible part of the spectral region covers the wavelength band corresponding to the plasma frequency for such plasma densities. Therefore, in this wavelength band a complete radiation reflection takes place from the NP plasma-water interface (a cutoff effect at the plasma frequency). It should be noted that the difference between the intensity values in the spectral region of 50 nm makes 30 times (from 2 to 0.07) that can not be an experimental error.

In these experiments the error of the intensity measurements by the repetition and in the meeting-points of measurements upon the transition into another spectral region does not exceed 10%.

The whole spectral region from 360 to 700 nm was photographed with the camera VFU-1 for 7 digits. Therefore, when the spectrum intensity is measured to determine the temperature one should use the spectral region of a more shortwave band than that of the wavelengths corresponding to the plasma frequency.

In the course of time (103 µs) the gradual temperature equalization occurs. At 153 µs the radiance temperature, measured in the wavelength band of 360 to 700 nm, is changing from $9\ 10^3$ K in the violet spectral region to (12…15) 10^3 K in the red spectral region (see Fig. 4) and the spectral radiation approaches to the ABB radiation. The number of tungsten absorption lines increases with time, and the lines of a higher upper level appear. In this case more and more levels appear onto which the recombination and de-excitation in a free-bound radiation spectrum is possible.

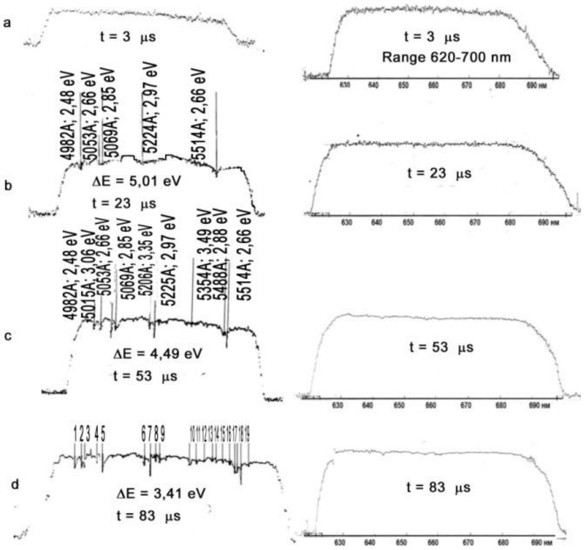


Fig. 4. Record of the spectrum for Tungsten wire explosion in two spectral regions Tungsten. - Tungsten 300 µm, 20 kV (d: 1 – 4982 A, 2,48 eV; 2 – 5006 A, 3.24 eV; 3 – 5015 A, 3.06 eV; 4 – 5053 A, 2.66 eV; 5 – 5069 A, 2.85 eV; 6 – 5206 A, 3.32 eV; 7 – 5224 A, 2.97 eV; 8 – 5242 A; 4.39 eV; 9 – 5254 A, 4,27 eV; 10 – 5354 A, 3.49 eV; 11 – 5368 A, 4.57 eV; 12 – 5391 A, 3.07 eV; 13 – 5413 A, 3.94 eV; 14–5435 A, 2.48 eV; 15 – 5463 A, 4.1 eV; 16 – 5477 A, 3.43 eV; 17 – 5488 A, 2.85 eV; 18 – 5514 A, 2.66 eV; 19 – 5528 A, 3.9 eV)

This happens upon significant decrease of both the pressure and the electron concentration in the plasma channel. Similar results are obtained by explosion of wires (Ø 160…500 µm) made from other metals (iron, copper, nickel, molybdenum). It is important that the larger diameter of the metallic wire, the longer duration of the plasma recombination. To compare the experimental results of radiance temperature measurements and the theoretical values the calculations on the adiabatic cooling of the expanding plasma channel have been performed. The adiabatic equation has the form of $P\ V^k$ =const [18]. In the case of the waster plasma it is k=1.26 [5]. Having the time dependence of the channel radius and shock wave front we calculate, by the formula for quasi-incompressibleliquid, the pressure in the plasma channel and its variation in time.

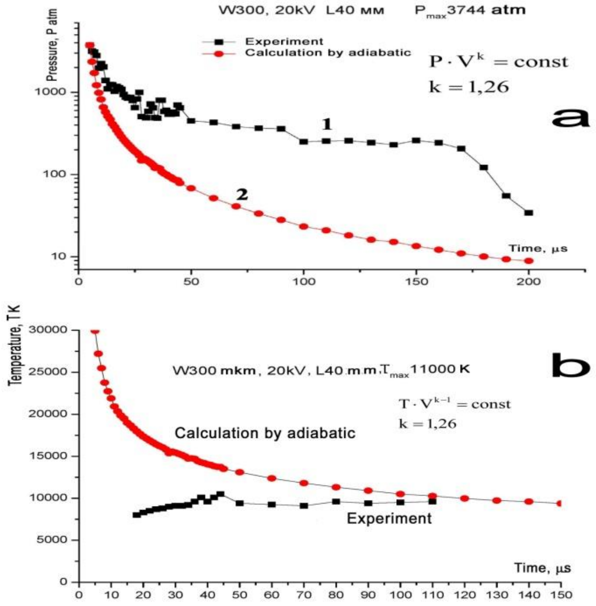


Fig. 5. The experimental 1 and calculated 2 depending sfor adiabatic expansion on pressure (a) and temperature (b) versus time

Fig. 5,a, curve 1 presents the calculation results. Using the maximum pressure and the time dependence of the channel radius the time dependence of the pressure for the adiabatic expansion is calculated (see Fig. 5,a, curve 2). The pressure values at the late plasma damping stages, calculated by the adiabat, are lower more than 20 times in comparison with the experimental values calculated by the formula for quasi-in-compressible liquid. The re-calculation of the temperature by the adiabat from the maximum value at the late plasma damping stage to the discharge initiation gives the values up to $T=3\ 10^4$ K, and the radiance temperature, observed at this instant of time in the red region, does not exceed $7\ 10^4$ K. These data indicate on the significant store in the plasma channel of the internal energy, the relaxation of which is hindered because of “unrealization” of many levels in the plasma microfields the value of which is comparable with intraatomic electric fields.

CONCLUSIONS

The distributions and the value of the radiation intensity being observed in the dense plasma (electron density $N_e \geq 10^{19}$ cm^{-3}), as a rule, does not corresponds to the temperature and concentration of the dense plasma.. This is related with “unrealization” of upper levels of radiation (absorption) of metal and gas atoms formed in the channel in high electric microfields arising in the dense plasma with high electron concentrations. This leads to the decrease in the number of levels, onto which the recombination should be possible, and a part of the processes of the radiation from the free-bound states is lost.

As a result, the continuous spectrum intensity sharply decreases. At electron concentration of $7\ 10^{21}$ cm^{-3} in the visible spectral region the radiation from the channel strongly depends on the plasma frequency. Disappearance of the radiation from the plasma channel at the instant of time with a maximum energy contribution into the plasma is caused by two effects. The first effect – “unrealization” of atomic levels in the intense microfields, related with high electron concentrationin the dense plasma, leads to the miss of the electron recombination onto these levels and to the radiation intensity decrease. The second effect is the “cutoff” of the radiation on the wavelengths corresponding to the plasma frequency and to the spectral region with longer wavelengths.

REFERENCES

1. E.A. Martin. Experimental investigation of a high-energy density high pressure arc plasma // *J. App. Phys.* 1960, v. 31, № 2, p. 255-267.
2. G.A. Bopp. Evaluation of the temperature in the channel of the pulsed discharge in liquids // *Optika i spektroskopiya*. 1965, v. 18, №3, p. 529-530 (in Russian).
3. L.L. Pasechnik, P.D. Starchik, O.A. Fedorovich. Temperature measurement for the plasma formed by the underwater wire explosion under conditions of developed instabilities in the discharge channel // *Collected Articles “Theory and Practice of the Electrohydraulic Effect*”. Kiev: “Naukova dumka”, 1978, p. 43-49 (in Ukrainian).
4. G.A. Gulyj, Yu.V. Korolyov, L.L. Pasechnik, P.D. Starchik, O.A. Fedorovich, I.S. Shvets. Plasma heating in the channel of a underwater high-power wire explosion // *Collected Articles “Theory and Practice of the Electrohydraulic Effect*”. Kiev: “Naukova dumka”, 1978, p. 36-42 (in Russian).
5. K.A. Naugonykh, V.A. Roj. *Electrical discharges in water*. M.: “Nauka”, 1971, p. 155 (in Russian).
6. G.A. Gulyj, I.S. Shvets, I.I. Kharichkhov. The time dependence of the surface temperature of the plasma channel created by the underwater electrical wire explosion on the discharge circuit parameters // *Collected Articles – “Discharge-pulsed technological processes”.* Kiev: “Naukova Dumka”. 1982, p. 8-13 (in Ukrainian).
7. L.L. Pasechnik, P.D. Starchik, O.A. Fedorovich. *Time evolution of radiation spectra of pulsed discharges in water “Theory, experiment, practice of the discharge-pulse technology”.* Kiev: “Naukova Dumka”. 1987, p. 6-9 (in Ukrainian).
8. J.M. Robinson. Measurement of plasma energy density and conductivity from 3 to 120 kbar // *J. Appl. Phys.* 1964, v. 7, № 6, p. 210-216.
9. P.M. Sherk. Temperatures of plasma product by exploding wires under water // *Phys. Fluids*. 1964, v. 7, № 6, p. 913-915.
10. R. Buntzen. Application of exploding wires for investigation of low-power underwater discharges // *Collected Articles „Electric explosion of wires*“. M.: “Mir”. 1965, p. 225-238 (in Russian).

11. O.A. Fedorovich, L.M. Voitenko. On NP damping coefficient caused by tungsten wire explosion in water // *PAST*. 2010, № 4, p. 354-359.

12. O.A. Fedorovich. On the plasma frequency effect on the continuous radiation spectrum of PDW in the visible region // *VANT. Seriya“Plazmennaya ehlektronika i novyye metody uskoreniya”* (6). 2008, № 4, p. 283-287 (in Russian).

13. O.A. Fedorovich. Empirical formula for the dependence of the “optical gap” value on the electron concentration N_e within the range of $10^{17}cm^{-3} \le n_e \le 10^{22}sm^{-3}$ // *Voprosy atomnoj nauki i tekhniki. Seriya “Plazmennaya ehlektronika i novyye metody uskoreniya”*. 2013, № 4, p. 223-228 (in Russian).

14. O.A. Fedorovich. Experimental investigations of NP optical properties in the electron concentration range 10^{17}см$^{-3} \le N_e \le 10^{22}cm^{-3}$ // *TVT*. 2014, v. 2, № 4, p. 524-534.

15. A. Grinenko, S. Efimov, A. Fedotov, and Ya.E. Krasik. Addresing the problem of wire format on around an exploding wire in water // *Physics. of Plasmas*. 2013, p. 0527031-0527036.

16. A.N. Demidov, N.N. Ogurtsova, I.V. Podmoshen -skij. Pulsed light source with radiation similar to the black body radiation at 40000 K // *Optiko-mekhanicheskaya promislennost*. 1960, № 1, p. 2-7 (in Russian).

17. *Plasma investigation methods. Edited by W. Lochte-Holtgreven.* M.: “Mir”. 1971, p. 552 (in Russian).

18. D. Ter Haar, H. Wergeland. *Elementary thermodynamics.* M.: “Mir’’ 1958, p. 219 (in Russian).

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ОБ ОСОБЕННОСТЯХ ИЗЛУЧЕНИЯ ИМПУЛЬСНЫХ РАЗРЯДОВ В ВОДЕ, ИНИЦИИРУЕМЫХ ТОЛСТЫМИ ПРОВОДНИКАМИ

О.А. Федорович, Л.М. Войтенко

Приводятся результаты исследований распределения интенсивности (I) излучения плазменного канала в видимом диапазоне. Канал импульсного разряда в воде инициируется взрывом проводника из W диаметром 300 мкм при начальном напряжении на батарее 20 кВ. I свечения поверхности канала не коррелирует с вкладом мощности в плазму. Вклад энергии заканчивается на 20 мкс, а максимум излучения сплошного спектра наблюдается на 80 мкс. I излучения практически не меняется в интервале времени от 50 до 120 мкс. Происходит «нереализация» уровней линейчатого спектра W вплоть до основного состояния. До 20 мкс излучение не удается зарегистрировать ($T_я \le 6\ 10^3$ К). Изучена динамика спектра линий поглощения во времени на участке спектра 490…560 нм, объясняющая увеличение интенсивности излучения с течением времени. В видимый диапазон излучения попадает область длин волн, соответствующая плазменной частоте. С течением времени наблюдается смещение области плазменной частоты в красную часть спектра и увеличение интенсивности излучения в фиолетовой области до значений, соответствующих $T = 2\ 10^4$ К. Происходит отражение излучения от границы канала на плазменной частоте. Проведено сравнение временной зависимости давления, полученного из расчетов по экспериментальным гидродинамическим данным и по адиабате. Видно сильное расхождение результатов. Такой же расчет для изменения T показывает, что на начальной стадии разряда T должна достигать значений $3\ 10^4$ К. Приведена динамика спектра излучения в области 620…700 нм. В области линии H_α (656,3 нм) до 83 мкм в спектре не наблюдаются линии ни поглощения, ни излучения.

ПРО ОСОБЛИВОСТІ ВИПРОМІНЮВАННЯ ІМПУЛЬСНИХ РОЗРЯДІВ У ВОДІ, ІНІЦІЮЄМИХ ТОВСТИМИ ПРОВІДНИКАМИ

О.А. Федорович, Л.М. Войтенко

Наводяться результати досліджень розподілу інтенсивності (I) випромінювання плазмового каналу у видимому діапазоні. Канал імпульсного розряду у воді ініціюється вибухом провідника з W діаметром 300 мкм при початковій напрузі на батареї 20 кВ. I випромінювання поверхні каналу не корелює з вкладом потужності в плазму. Вклад енергії закінчується на 20 мкс, а максимум випромінювання суцільного спектра спостерігається на 80 мкс. I випромінювання практично не змінюється в інтервалі часу від 50 до 120 мкс. Відбувається «нереалізація» рівнів лінійчатого спектра W аж до основного стану. До 20 мкс випромінювання не вдається зареєструвати ($T_я < 6 \cdot 10^3$ К). Вивчена динаміка спектра ліній поглинання в часі на ділянці спектра 490…560 нм, що пояснює збільшення інтенсивності випромінювання з часом. У видимий діапазон випромінювання потрапляє область довжин хвиль, яка відповідає плазмовій частоті. З плином часу спостерігається зміщення області плазмової частоти в червону частину спектра і збільшення інтенсивності випромінювання в фіолетовій області до значень, відповідних $T = 2 \cdot 10^4$ К. Відбувається відбиття випромінювання від кордону каналу на плазмовій частоті. Проведено порівняння часової залежності тиску, отриманого з розрахунків за експериментальними гідродинамічними даними і по адіабаті. Видно сильну розбіжність результатів. Такий же розрахунок для зміни T показує, що на початковій стадії розряду T повинна досягати значень $3 \cdot 10^4$ К. Наведено динаміку спектра випромінювання в області 620…700 нм. В області спектра лінії H_α (656,3 нм) до 83 мкм не спостерігаються лінії ні поглинання, ні випромінювання.