# DYNAMICS OF THE EMISSION SPECTRUM OF THE HYDROGEN-OXYGEN PLASMA OF PULSED DISCHARGE IN WATER IN THE RANGE OF THE BALMER SERIES WITH A MINIMUM OF IMPURITIES

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The results of experimental investigations of the spectral distribution of radiation of hydrogen - oxygen plasma pulsed discharges in water in a minimum difference of radiation from the blackbody radiation (BBR) are given. The pressure in the plasma channel was changed from 5000 to 80 atm, the brightness temperature of $24 \cdot 10^3$ to $7 \cdot 10^3$ K. The difference in brightness temperatures of the violet and the red area does not exceed ± 2000 K of the average temperature. With the relaxation of plasma electron density decreased from $2 \cdot 10^{20}$ to $10^{17}$ cm$^{-3}$. It is shown that at high concentrations of electron spectral distribution of the radiation in the spectral range of the Balmer series differs little from the blackbody radiation is not observed and none of the hydrogen Balmer line. This indicates "non-realization" even the top level line $H_{\alpha}$ (656.2 nm, with excitation energy of the upper level of 12.09 eV). As the relaxation of the plasma to be consistent line $H_{\alpha}$, $H_{\beta}$, $H_{\gamma}$. There is a redistribution of the broadening of the hydrogen lines of the Balmer series. At $N_e \le 10^{17}$ cm$^{-3}$ hydrogen emission spectrum coincides with the traditional.

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## INTRODUCTION

Optical radiation nonideal plasma is practically the only source of information on plasma parameters, the structure of the plasma channel, the mean free path of photons, radiant thermal conductivity, line broadening in a plasma, "optical reduction of the ionization potential", reducing the oscillator strengths, "non-realization" of individual, high-lying levels, and so on [1]. The study of the spectral distribution of radiation is necessary for the calculation of the energy and the particles balance in the channel of a pulsed discharge in water, revealing the influence of non-ideal effects on the emission spectra of hydrogen-oxygen plasma, the development and testing of the methods for measuring the basic plasma parameters and to identify the range of applicability of these methods depending on the electrons concentration in the plasma. The hydrogen-oxygen plasma produced in a pulsed discharge in water (PDW) on 2/3 is composed of atoms and ions of hydrogen. It is one of the significant advantages in the study of such plasma to determine the effects of nonideality influence on the emission spectra and their dependence on the electron concentration and temperature.

The spectrum hydrogen is the simplest for theoretical description as a hydrogen atom consists of a single electron and proton. But the published data on the hydrogen spectra at high electron densities are insufficient and they often contradictory (see in particular [2 - 8]). This is due to the fact that these data have been obtained at essentially different research facilities parameters, different methods of nonideal plasma obtaining and different initial conditions. Theoretical estimates of the non-ideal properties of the plasma are given in (see in particular [1, 10, 12]).

This paper presents the results of experimental investigations of the spectral distribution of radiation of hydrogen-oxygen plasma, and the evolution of the emission spectra at the stage of relaxation, depending on the temperature and on the optical thickness reducing. Also, presents the results of testing of different methods to determine the main parameters of the plasma.

One technique for obtaining spectral scans over time and the dynamics of the emission spectrum of the hydrogen-oxygen plasma in the PDW, in the $H_{\alpha}$, $H_{\beta}$ lines region, was considered in [6, 13]. A second technique for obtaining spectra scans in time and space, as well as calibration of the film in intensity from source EV-45 [14] is given in [15].

Previously, it was noted that in the initial stage of the discharge emission of the hydrogen-oxygen plasma essentially differs from the black body (BB) radiation [3]. The violet region of the spectrum there was a significant exceeding of brightness temperature $T_b$ measured in the red region of the spectrum. The degree of difference from the BB radiation increases with the rate of energy input into the plasma channel.

## EXPERIMENTAL RESULTS AND DISCUSSION

For studies was selected the discharge mode in which there is the smallest deviation of the radiation from the BB radiation.

The emission spectrum of the investigated plasma in the initial stage of discharge is continuous, and the intensity changes are little over time. With the expansion of the plasma channel, and with the decrease in its electrons concentration and pressure, a continuous spectrum of radiation is transformed into a line spectrum, and the duration of the last essentially depends on the energy input into the channel [15].

This reduces the optical thickness of the plasma and plasma becomes optically transparent [16, 17].

Let us consider in more detail the dynamics of the spectrum in the Balmer lines $H_{\alpha}$, $H_{\beta}$, $H_{\gamma}$ in near and-threshold region for one discharge regime and estimate influence on the spectrum of non-ideal effects. Figs. 1-8 shows the spectral radiation distribution of the hydrogen-oxygen plasma at different times, as the relaxation of the plasma. To do this, select the category with a minimal amount of metal impurities (emission spectrum which often leads to the inability to obtain lines of hydrogen [15]).

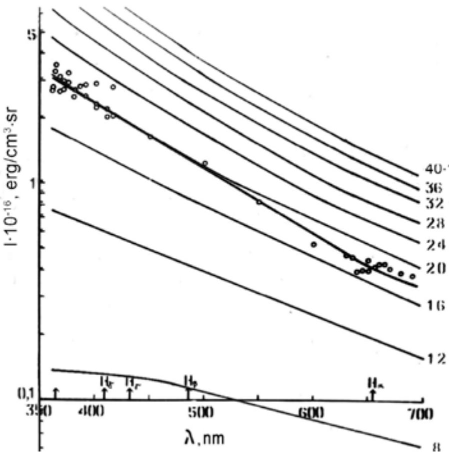


*Fig. 1. The intensity of the radiation I = f (λ) hydrogen-oxygen plasma in the Balmer series.* W, *d = 20 μm; $U_0$ = 30 кV; $l_0$ = 100 mm; t = (9 ± 2) μs*

To eliminate the influence of impurities of metal vapors coming from the electrodes [15] we chosen for study the spectrum of the discharge with electrode gap length 100 mm and investigated the middle of the channel.

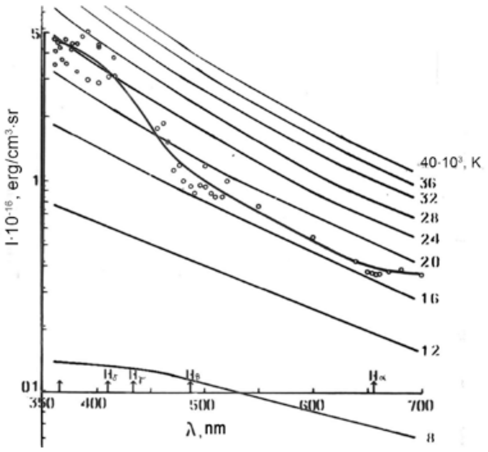


*Fig. 2. The dependence of the radiation intensity I = f (λ) hydrogen-oxygen plasma.* W, *d = 20 μm; $U_0$ = 30 кV; $l_0$ = 100 mm; t = (12 ± 2) μs*

As follows from Fig. 1 the emission spectrum of the hydrogen-oxygen plasma at an initial stage of the discharge (9 ± 2) microseconds) differs little from the blackbody radiation at a temperature (20 ± 1)·$10^3$ K. In near and-threshold region, as well as in the area of the most intense spectral $H_\alpha$ lines of hydrogen Balmer series no singularities of the spectrum is observed.

The plasma pressure, calculated by the hydrodynamic characteristics of the channel and model of quasi-incompressible fluid is ~ 2·$10^3$ at, and the electron density is less than $N_e \sim 5\cdot10^{19}$ cm$^{-3}$ at a concentration of atoms $N_a \sim 5\cdot10^{20}$ cm$^{-3}$ [18].

In the wall region of the plasma channel is always a colder region. The degree of ionization of the plasma in the colder region not exceeding 10%, and at this temperature there is always excited hydrogen atoms. In this case, inevitably had be observed in the absorption lines of hydrogen $H_\alpha$ (λ = 656.2 nm). However, as shown in Fig. 1, this does not occur, which indicates the manifestation of the effect of "non-realization" of the upper level of the most intense line of the Balmer series.

Over time, as the pressure reduction in the emission intensity at the spectrum-threshold and begins to rise somewhat, while in other areas it is somewhat reduced (Fig. 2), (t = (12 ± 2) μs). To detect absorption in the $H_\alpha$ line also fails. At the time (t = (22 ± 2) μs) is already clearly seen in the absorption line $H_\alpha$ (Fig. 3).

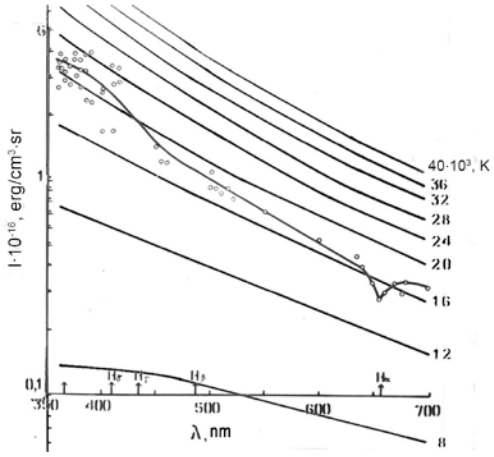


*Fig. 3. The dependence of the radiation intensity I = f (λ) hydrogen-oxygen plasma.* W, *d = 20 μm; $U_0$ = 30 кV; $l_0$ = 100 mm; t =(22 ± 2) μs*

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At the time (t = (22 ± 2) μs) is already clearly seen in the absorption line $H_\alpha$ (see Fig. 3). The intensity of the emission spectrum in the supercritical region corresponds to (22 ± 2)·$10^3$ K. If at the same time to measure the temperature in the center of the reabsorb line $H_\alpha$ it is ~14.5·$10^3$ K. The pressure in the plasma channel at the same time about ~ 300 at and $N_e$ ~ 3 ing of lines which are at a higher power level in comparison with the calculated.

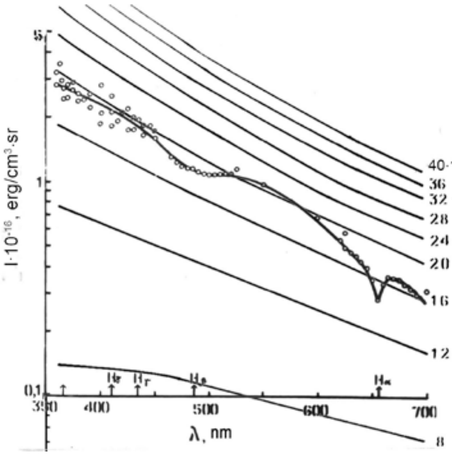


*Fig. 4. The dependence of the radiation intensity*
*I = f (λ) hydrogen-oxygen plasma.* W, *d = 20 µm;*
*$U_0$ = 30 кV; $l_0$ = 100 mm; t = (48 ± 2) µs*

These results indicate an inaccuracy of theoretical calculations of line broadening at high values of the micro-fields [15], in spite of the Debye screening accounting for the electron and ion components and the line broadening at high concentrations.

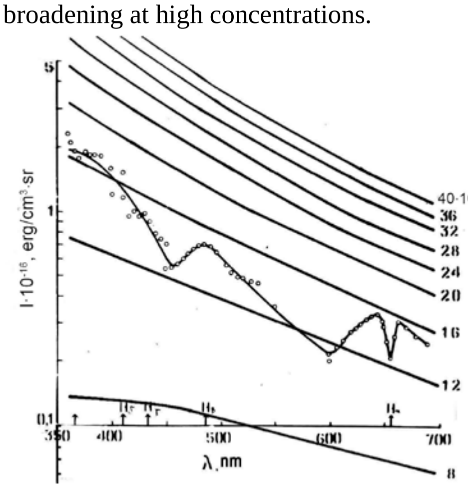


*Fig. 5. The dependence of the radiation intensity*
*I = f (λ) hydrogen-oxygen plasma. tungsten, d = 20 µm;*
*$U_0$ = 30 кV; $l_0$ = 100 mm; t =(57 ± 2) µs*

As already noted, the pressure drop as the optical thickness and temperature of the plasma decreases and continuous emission spectrum is transformed into a line spectrum. Fig. 5 shows the emission spectrum of the hydrogen-oxygen plasma, when the lines $H_\alpha$, $H_\beta$, $H_\gamma$ become prominent in a continuous spectrum of radiation. The optical thickness in the distant wing of the line $H_\alpha$, is reduced to τ = 1.5…2 [13, 17].

Note that the values of τ, obtained by the method of plasma transillumination under PRW give overestimated 5…8 times values. This is due to the passage of the rays through the plasma. Plasma is in the water with a refractive index n = 1.34, while for n = 1 the plasma [20]. This cylindrical plasma channel works as a cylindrical lens.

Given that the boundary of the channel are not always strictly cylindricity due to instabilities of the plasma channel is correctly taken into account in determining the curvature of the intensity of the transmitted beam is not possible.

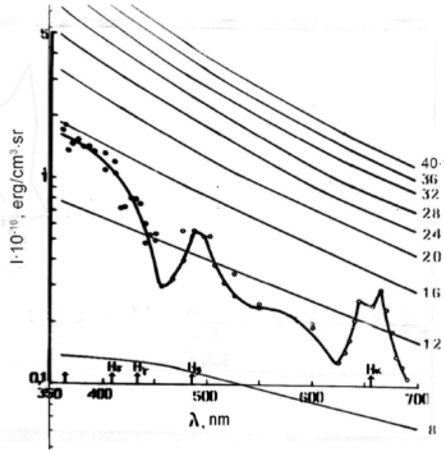


*Fig. 6. The dependence of the radiation intensity*
*I = f (λ) hydrogen-oxygen plasma.* W, *d = 20 µm;*
*$U_0$ = 30 кV; $l_0$ = 100 mm; t = (64 ± 2) µs*

Because of this value of τ, obtained by the method transillumination essentially overestimated and they can not be used, although plasma is possible to enlighten in the later stages the discharge.

In violet part of the continuous spectrum of the value of τ should be even smaller. The parameters of the plasma channel, defined by several independent methods are: P = 120 bar, $N_e = 10^{19}$ cm$^{-3}$, T = $17 \cdot 10^3$ K. At the same time temperature as determined by the intensity at the maximum reabsorbs line $H_\alpha$ [13] and in the threshold of the Balmer series of the spectrum are the same. The temperature obtained by I for the line $H_\beta$ somewhat higher.

A characteristic feature of the emission spectrum is the fact that the half-width of the line $H_\alpha$ more than $H_\beta$ and $H_\gamma$, although according to the theory of line broadening [15] should be the opposite. The same effect is observed upon further reduction of P and T (Fig. 6). Here the half-width of the line $H_\alpha$, $H_\beta$ is 150, 140 A, $H_\gamma$ 65 A. The optical thickness in the red region of the continuous spectrum τ < 1 [15].

Therefore, the effect of the near-wall cold regions of the plasma can be neglected. They partially affect reabsorption in the central region of the line Hα, where τ more (τ > 10), but their influence on the radiation in the violet part of the spectrum should be negligible.

The parameters of the plasma channel are follows: P = 100 atm, $T_{max} = 15.5 \cdot 10^3$K, $N_e = 6 \cdot 10^{18}$ cm$^{-3}$, the bore diameter d = 23.4 mm.

In Figs. 7, 8 show the dynamics of the emission spectrum at lower plasma concentrations and low temperatures. These figures show that the half-width of the lines $H_\alpha$ and $H_\beta$ are compared, and then, when at $N_e \leq 2 \cdot 10^{17}$ cm$^{-3}$ lines $H_\beta$ are wider than $H_\alpha$, as predicted by the theory [19], and the values of $N_e$, obtained by the half-widths of these lines are virtually identical. Decreases while the intensity $H_\beta$ line and T defined poney becomes smaller than defined by certain intensity in $H_\alpha$, which could be evidence of small optical thickness in line $H_\beta$.

In the adjacent and threshold areas of the series spectrum regions intensity is slightly higher than in other areas.

In the near-threshold areas and threshold areas a series of intensity of the spectrum is somewhat higher than in other areas. Line $H_\gamma$ observed only a few microseconds, and its half width is less than $H_\beta$. microseconds, and its half width is less than the line $H_\beta$ [5, 6]. Line $H_\delta$ from the continuous spectrum was unable to locate.

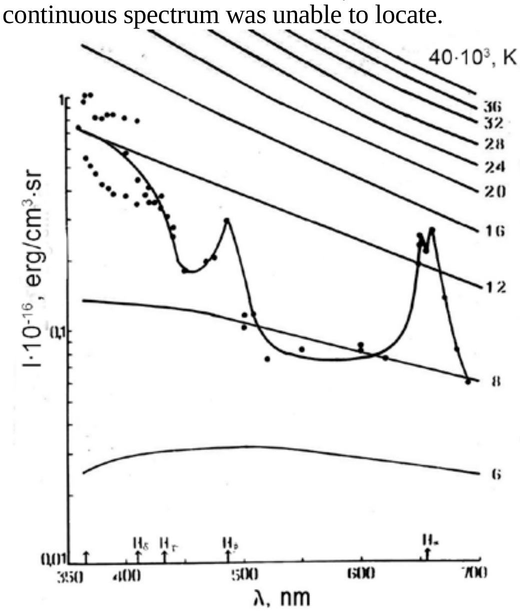


*Fig. 7. The dependence of the radiation intensity $I = f(\lambda)$ hydrogen-oxygen plasma. W, d = 20 μm; $U_0$ = 30 кV; $l_0$ = 100 mm; t =(71 ± 2) μs*

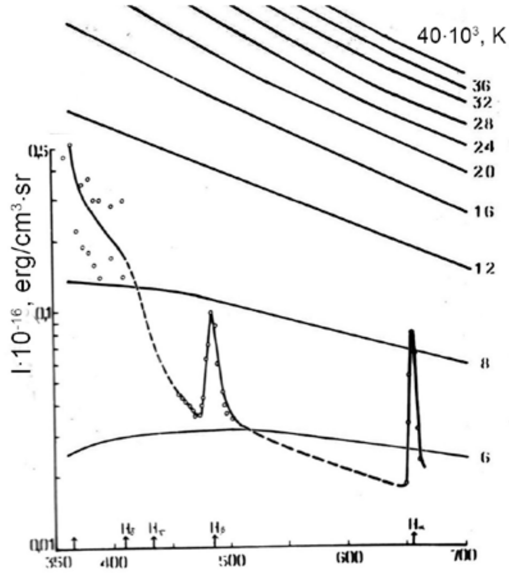


*Fig. 8. The dependence of the radiation intensity $I = f(\lambda)$ hydrogen-oxygen plasma. W, d = 20 μm; $U_0$ = 30 кV; $l_0$ = 100 mm; t = (86 ± 2) μs*

Note that if the appearance of lines $H_\beta$, and $H_\gamma$ responsible colder outer region of the plasma, the effect of reducing the line broadening is even stronger. To detect the influence of this effect it is necessary to obtain the radial distribution of the temperature and make intensity correction taking into account the refraction at the plasma-water interface.

In [20] the radial temperature distribution for this mode of discharge by 77 ms. It shows almost plateau-like temperature distribution along the radius (cross section) of the channel, which should not significantly affect the electrons distribution and concentration in the channel cross section and the absorption in the near-wall plasma regions.

According to [10, 11] $H_\alpha$ line should "not be realized" when the electron density $N_e \geq 2\cdot10^{19}$ cm$^{-3}$, $H_\beta$ when $N_e \geq (1.5…3)\cdot10^{18}$ cm$^{-3}$, $H_\gamma$ when $N_e \geq 0.9\cdot10^{18}$ cm$^{-3}$. These $N_e$ values are somewhat lower than those obtained experimentally by several methods [20].

Perhaps this is due to colder regions near the walls, and realization of the lines with higher levels just in them.

The above results indicate a decrease or redistribution of oscillator strength, predicted in [21], and the "non-realization" of lines level in the micro-fields, comparable in magnitude to the strength of intra-atomic fields, and in this range includes most intense level of $H_\alpha$ lines.

## CONCLUSIONS

The plasma parameters can be measured outside the boundaries of the series or on lines that are not affected by non-realization, as predicted theoretically in [5, 6]. Especially strongly last effect is manifested with increasing rate of energy input into the channel [3].

From the above results and results in [13] it can also be concluded that it is permissible to determine the electron density from the Stark broadening of the lines $H_\alpha$ when $N_e < 10^{19}$ cm$^{-3}$ and $H_\beta$ when $N_e < 10^{18}$ cm$^{-3}$.

To measure the maximum temperature along the line monitoring the intensity of the radiation maximum $H_\alpha$ line can be reabsorbed immediately after discharge from the continuous spectrum.

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## ДИНАМИКА СПЕКТРА ИЗЛУЧЕНИЯ ВОДОРОДНО-КИСЛОРОДНОЙ ПЛАЗМЫ ИРВ В ДИАПАЗОНЕ СЕРИИ БАЛЬМЕРА С МИНИМАЛЬНЫМ КОЛИЧЕСТВОМ ПРИМЕСЕЙ

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Приведены результаты экспериментальных исследований спектральных распределений излучения водородно-кислородной плазмы импульсных разрядов в воде (ИРВ) в условиях минимального отличия этого излучения от излучения абсолютно черного тела (АЧТ). Давление в плазменном канале менялось от 5 тыс. атмосфер до 80 атмосфер, яркостная температура от $24{\cdot}10^3$ до $7{\cdot}10^3$ К. Различие яркостных температур в фиолетовой и красной областях не превышало ± 2000 К от средней температуры. При релаксации плазмы концентрация электронов уменьшалась от $2{\cdot}10^{20}$ до $10^{17}$ см$^{-3}$. Показано, что при высоких концентрациях электронов спектральное распределение излучения в диапазоне спектра серии Бальмера мало отличается от излучения АЧТ и не наблюдается ни одна линия водорода серии Бальмера. Это свидетельствует о «нереализации» даже самого верхнего уровня линии $H_\alpha$ (656,2 нм, с энергией возбуждения верхнего уровня 12,09 эВ). По мере релаксации плазмы проявляются последовательно линии $H_\alpha$, $H_\beta$, $H_\gamma$. Наблюдается перераспределение уширения линий водорода серии Бальмера. При $N_e \le 10^{17}$ см$^{-3}$ спектр излучения водорода совпадает с традиционным спектром.

## ДИНАМІКА СПЕКТРА ВИПРОМІНЮВАННЯ ВОДНЕВО-КИСНЕВОЇ ПЛАЗМИ ІРВ У ДІАПАЗОНІ СЕРІЇ БАЛЬМЕРА З МІНІМАЛЬНОЮ КІЛЬКІСТЮ ДОМІШОК

***О.А. Федорович, Л.М. Войтенко***

Наведено результати експериментальних досліджень спектральних розподілів випромінювання водневокисневої плазми імпульсних розрядів у воді (ІРВ) в умовах мінімальної відмінності випромінювання від випромінювання абсолютно чорного тіла (АЧТ). Тиск у плазмовому каналі змінювався від 5 тис. атмосфер до 80 атмосфер, яскравістна температура – від $24{\cdot}10^3$ до $7{\cdot}10^3$ К. Різниця яскравісних температур у фіолетовій і червоній областях не перевищувала ± 2000 К від середньої температури. При релаксації плазми концентрація електронів зменшувалася від $2{\cdot}10^{20}$ до $10^{17}$ см$^{-3}$. Показано, що при високих концентраціях електронів спектральний розподіл випромінювання в діапазоні спектра серії Бальмера мало відрізняється від випромінювання АЧТ і не спостерігається ні одна лінія водню серії Бальмера $H_\alpha$. Це свідчить про «нереалізацію» навіть самого верхнього рівня лінії $H_\alpha$ (656,2 нм, з енергією збудження верхнього рівня 12,09 еВ). По мірі релаксації плазми проявляються послідовно лінії $H_\alpha$, $H_\beta$, $H_\gamma$. Спостерігається перерозподіл розширення ліній водню серії Бальмера. При $N_e \le 10^{17}$ см$^{-3}$ спектр випромінювання водню збігається з традиційним.