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MEASUREMENT OF THE MAIN PARAMETERS OF A HIGH-PRESSURE, HYDROGEN–LITHIUM PLASMA

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The pressure along the capillary length, its dependence on the capillary diameter, the time dependences of the temperature and pressure, and the radial dependences of the temperature are measured in a capillary discharge with a vaporizing wall (material: lithium hydride).

The interest in the investigation of the optical properties of gases at temperatures of tens of thousands of degrees is connected with the clarification of the role of radiant energy transfer in a number of phenomena: electric arcs, shock waves developing upon the entry of a body into the earth's atmosphere with a hypersonic velocity, a laser flash, etc. Thanks to the self-similarity of Coulomb properties, data on plasma properties in a model range convenient for experiment can be carried over to another natural region of parameters.

To investigate the properties of a high-pressure, hydrogen–lithium plasma we used a capillary discharge with a vaporizing wall (CDVW), developed at the State Optical Institute [1], permitting the obtainment relatively simply and for a sufficiently long time (~500 μsec) of a plasma of known composition in a wide pressure range, from 10 to 500 bar, at temperatures on the order of 4 eV.

During the passage of a current pulse through a capillary the space of the capillary is filled with material violently vaporized from the walls. The dissociation and then the ionization of the vaporized material occur, and a high-pressure plasma, at tens or hundreds of atmospheres, forms in the capillary. Simultaneously with vaporization of the wall in a CDVW one observes the escape of plasma jets through the open ends of the capillary, with the gas which initially filled the capillary, open to the atmosphere, being entirely displaced and only the elements entering into the composition of the wall remaining in the discharge. It has been established [2] that in forced modes of discharge the quantitative ratios of elements in the solid and gaseous phases coincide. This property of a CDVW is extremely attractive for obtaining a plasma of a given composition, since usually in installations of any type the plasma is contaminated by impurities entering the discharge from the walls and from the electrodes. Lithium hydride served as the working substance.

The installation consisted of an airtight chamber mounted on an optical track and a unit for supplying rectangular current pulses. Briquettes of lithium hydride were pressed into a Textolite casing. Rods 9 mm in diameter made of fine-grained graphite of spectral purity were used as the electrodes. In those experiments where it was necessary to measure the pressure, the LiH briquette was placed in a cylindrical Textolite plug and was pressed from the open end by a metal cylinder, which simultaneously served as the current-carrying electrode. The working LiH briquettes were obtained by pressing them from powder with a particle size of not more than 0.2 mm at a pressure of 9.5 tons/cm^2. The percentage content of impurities in the working substance was: Na 0.06, Mg 0.06, SiO_2 0.02, Ca 0.01. The supply unit of the installation included an artificial LC-line ($L = 8$ μH, $C = 150$ μF × 5 kV).

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a charging device, a circuit for measuring the discharge current, and a discharge-trigger circuit.

The pressure in the CDVW was determined by the geometry factor Φ/l of the capillary, the value of the current, and the wall material. The crusher, piezoelectric, and spectroscopic* method were used to measure the pressure in the plasma. The results of a dynamic calibration of the crusher sensor carried out by V. G. Muravenko using a dropping load were used to determine the pressure. The values of the pressure in the capillary measured by the crusher method as a function of the capillary diameter are presented in Fig. 1 (J = 5-6 kA). An important parameter of a CDVW is the law of pressure variation along the length of the capillary. In Table 1 we present this dependence ($P/P_{max} = f(l)$) for three capillary diameters: 2, 2.5, and 3 mm. As the measurement results showed, this dependence hardly varies in the range of capillary diameters of 2-6 mm.

The time dependence of the continuous-emission intensity $I^c_\lambda = f(t)$ was used to determine the time dependence of the pressure under the assumption that the coefficient of continuous absorption is $k^c_\lambda \sim p^2$ at constant temperature. The time maximum of the pressure was determined from the readings of the crusher sensor. In principle the time resolution in measuring the pressure did not exceed the 4-μsec time resolution of the photographic time sweep of the spectrum.

A disk of barium titanate, to which a zinc rod having an acoustic impedance equal to that of the barium titanate was cemented, was used as the sensitive element of the piezoelectric sensor. The theoretical resolution of the sensor, estimated from the ratio of the thickness of the barium titanate disk to the speed of sound in it, was $\tau \approx 3 \cdot 10^{-7}$ sec. Typical curves of pressure variation obtained by the piezoelectric and spectroscopic methods are presented in Figs. 2 and 4, respectively. The trends of the curves obtained by the two different methods approximately coincide. The pressure rise at the start of a pulse is connected with the violent vaporization of the wall material. The subsequent decline in pressure is evidently connected with an increase in the diameter due to its combustion and with a small decrease in the current.

In the present work the quality of the composition of the capillary plasma and of the plasma jets was studied and the main parameters of the plasma were determined by spectral methods. The emission spectra were photographed in the wavelength region of 2300-9000 Å. In the photography an image of the capillary was projected onto the spectrograph slit, the center of the capillary coinciding with the center of the slit. Spectra were also photographed "from the side," in the direction perpendicular to the capillary axis. In this case the photographs were made in the absence of long plasma jets, which made it possible to obtain information about the emission in the discharge channel.

The investigated source possesses a uniform continuous spectrum with a number of absorption and emission lines. Lines of the atoms and ions entering into the composition of the material of the wall and the electrodes — Li, H, Mg, Na, C, and Ca — and lines of elements emitted in the jets (O, N, etc.) are present in the spectrum. Oxygen lines also appear in the discharge spectra owing to oxidation of the surface layer of lithium hydride in air. These lines usually disappear 50-150 μsec after the start of the discharge, which can be observed in time sweeps of a spectrum. All the most intense lines of the principal and the first and second subordinate series of the lithium atom are observed in the absorption spectrum, as well as the 6240 Å Li I forbidden line. Of the hydrogen lines only H_α and H_β are clearly observed against the background of the continuous spectrum at high pressures in the discharge ($p \gtrsim 100$ bar); the remaining lines of the Balmer series are extremely broadened and merge with the background. At "low" pressures ($p \approx 10$ bar), conversely, the emission is determined to a considerable extent by the hydrogen lines, despite the high temperatures of CDVW. Reversed lines prove to be common for spectra of the capillary and of the plasma jets. The intense 5484.7 Å Li II line of the lithium ion with an excitation potential $E_m = 61.28$ eV is observed in emission, which indicates a high temperature in the discharge channel.

A time sweep of the spectra was used for the quantitative measurements, since the plasma being studied reveals time variation of the intensity of the continuous and line emission. To obtain the sweep the spectra were photographed on film fastened to a rotating drum which served as an attachment to an ISP-51 spectrograph with an f = 270 mm camera and was mounted in the focal plane of the camera objective. A high-speed sweep of the spectrum for the mode

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*The constructions of the crusher and piezoelectric sensors were developed by A. V. Klimov.

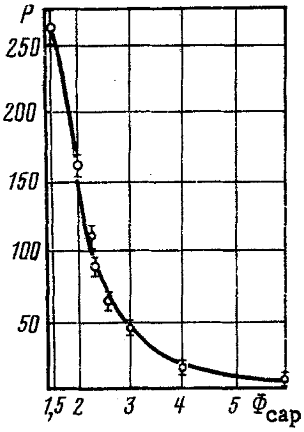

Fig. 1

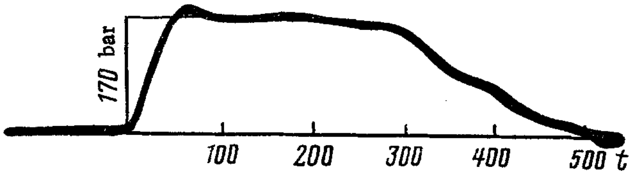

Fig. 2

Fig. 1. Dependence of pressure P, bar, on capillary diameter Φ, mm; l_{cap} = 1 cm, J = 5-6 kA.

Fig. 2. Oscillogram of pressure obtained with the piezoelectric sensor; Φ_{cap} = 2 mm, l_{cap} = 1 cm, J = 5.1 kA, t, μsec.

TABLE 1. Pressure Variation along the Length of Capillary

l, mm	Φ_{cap}=2 mm	Φ_{cap}=2,5 mm	Φ_{cap}=3 mm
0,4	0,29	0,4	0,35
1,4	0,45	0,53	0,68
2,8	0,9	0,95	0,84
3,4	0,93	—	—
5	1,0	1,0	1,0

of Φ_{cap} = 1.5 mm is presented in Fig. 3. The duration of the leading front of a pulse is 40-50 μsec and that of the trailing front is ~110 μsec. The predominance of the line spectrum of air is characteristic of the leading front of a pulse, i.e., at first the air has still not been displaced from the capillary. The maximum continuum intensity and the broadening of the 5484 Å Li II, H_α, and H_β lines occur immediately behind the leading front of a pulse, and then these quantities decrease. The width of the absorption lines of lithium atoms increases with time. Prolonged after-emission of the lithium and hydrogen lines is observed, belonging to the plasma jets.

From the estimates and measurements of the optical depths it was found that for modes with $p \approx 10$-120 bar the temperature can be measured from the absolute intensity of the 5484.7 Å line of the lithium ion. This line was chosen for diagnostics from the following considerations: the self-absorption of the line due to the high excitation potential is not too great, while its intensity is sufficient for reliable recording above the background; $E_m \gg kT$, which is a condition for high-precision temperature measurements; no other strong emission or absorption lines are near; this line is the only one observed in emission during practically the entire pulse, which permits its use for measuring time dependences of the temperature.

The temperature was determined from the usual equations by the absolute-intensity method. The conditions of total local thermodynamic equilibrium (LTE) for the lithium ion are satisfied starting with $p \simeq 20$ bar and $T \simeq 4$ eV. The conditions of partial LTE for levels of the lithium ion with $n \geqslant 2$ are well satisfied in the plasma under investigation. The probability of the 5484.7 Å Li II transition is $A_m^n = 2.28 \cdot 10^7$ sec^{-1} with an accuracy of 3% [3]. The concentration of lithium ions was determined from the data of a thermodynamic calculation made for a plasma of a given composition with allowance for the decrease in the ionization potential in the linear Debye approximation. The statistical sum for the lithium ion, calculated from the equation $Q(T) = \Sigma g_n \exp[-E_m/kT]$ for all the modes investigated, proved to equal one, the statistical weight of the ground state, with an accuracy of 0.001.

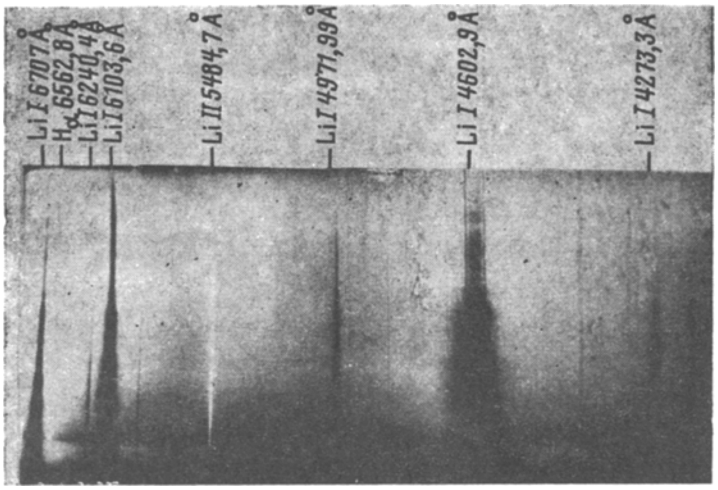

Fig. 3. Spectrogram of capillary emission for the mode of Φ_{cap} = 1.5 mm, l_{cap} = 1 cm, J = 5 kA.

The 5484.7 Å Li II line, which is a triplet, proved to be unresolvable under thermal excitation in the plasma, and was treated as one line in the analysis. The absolute intensity was measured by the photographic method. An ÉV-45 source with T_b = 41,000°K was used as the standard. The main temperature measurements were made from time-swept spectrograms for the central part of the capillary. Since the conditions of an optically thin layer were not satisfied for the 5484.7 Å Li II line for all modes of operation of the installation, direct measurements of the optical depth in the line were made.

The total emission energy with allowance for the continuum is

$$I_\lambda = B_\lambda (1 - \exp[-k^c_\lambda l]) + \exp[-k^c_\lambda l] (1 - \exp[-k^\partial_\lambda l]) B_\lambda, \qquad (1)$$

which also makes it possible to estimate the influence of the continuum on the line intensity. The procedure for measuring the absolute line intensity was the following; the quantity $I^\partial_\lambda = B_\lambda(1 - \exp[-k^\partial_\lambda l])$ was determined from the total measured intensity by Eq. (1), then a correction was introduced for self-absorption, and a reduction was made to an optically thin layer using the equation

$$I_{\lambda\,\mathrm{otl}} = I^\partial_\lambda \frac{k^\partial_\lambda l}{1 - \exp[-k^\partial_\lambda l]}.$$

In this case the temperature was determined by the method of successive approximations. The values of the corrections $\exp[-k^c_\lambda l]$ and $k^\partial_\lambda l/(1 - \exp[-k^\partial_\lambda l])$ were not too large (the maximum values for the mode of p = 115 bar were 0.55 and 1.6, respectively). In measuring the line intensity from the end of the capillary we allowed for the contribution of the jet by obtaining the coefficients of emission of the jet at different distances from the end of the capillary and integrating it over the length of the jet.

In measuring the time dependences of the temperature in the capillary the temperature was first measured at the moment of maximum pressure. To allow for the pressure variation along the length of the capillary, it was divided into 10 zones, in each of which the pressure was assumed to be constant, and the calculated value of the intensity of the 5484.7 Å Li II line was determined as a sum over these sections. The temperature at the moment of maximum pressure proved to be practically the same for different modes (~50,000°K). Typical curves of the time dependence of the temperature and pressure are presented in Fig. 4. The temperature grows appreciably after the moment of maximum pressure and then usually grows by 2000-3000°K during a pulse, although this growth does lie within the limits of the experimental errors.

The error in measuring the temperature is estimated with allowance for the inaccuracies in determining the absolute emission intensity (±40%), the ion concentration (±25%), the transition probability (±10%), and the length of the emitting layer (±10%). With these values the error in measuring the temperature is ±6%. Thus, the temperature of a capillary dis-

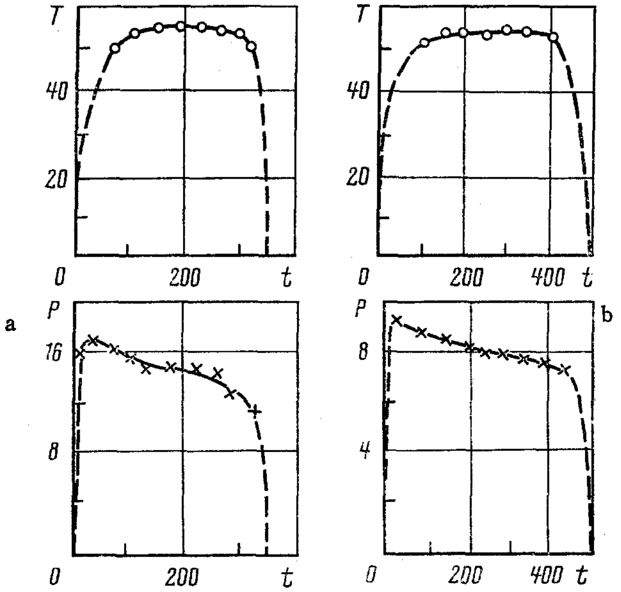

Fig. 4. Dependence of temperature t, 10^3°K, and pressure P, bar, on time t, μsec, for modes of $\Phi_{cap} = 4$ mm and J = 5.8 kA (a) and $\Phi_{cap} = 6$ mm and J = 6 kA (b); $l_{cap} = 1$ cm.

TABLE 2. Radial Temperature Variation

Φ_{cap}=3 mm	d/Φ_{cap}	0,04	0,12	0,18	0,26	0,35	0,46	0,58	0,65	0,73	0,83	0,93
	T, °K	41000	49000	52000	53200	54000	54500	53800	53400	52000	51800	42000
Φ_{cap}=4mm	d/Φ_{cap}	0,07	0,12	0,23	0,31	0,41	0,47	0,61	0,68	0,76	0,87	0,92
	T, °K	48000	50700	51800	53000	53500	55000	54600	54000	52600	50500	46000

charge with a vaporizing wall of LiH is practically constant in time, the maximum departures comprising no more than 3000-4000°K. Larger departures are observed only at the leading and trailing fronts, where the temperature declines.

The radial temperature dependence obtained from spectrograms, not swept in time, by the method described above is presented in Table 2 ($l_{cap} = 1$ cm).

The temperature field is characterized by a high temperature gradient in the boundary region. At the center of the capillary the temperature varies little, declining by only 10% at $d = 0.8\Phi_{cap}$.

NOTATION

d, Coordinate along abscissa; l, length of capillary; J, current; I_λ^c, continuous emission at wavelength λ; k_λ^c, coefficient of continuous absorption; p, pressure; τ, resolving power of piezoelectric sensor; E_m, excitation potential; f, focal length; T, temperature; A_m^n, probability of the transition m → n; Q(T), statistical sum; g_n, statistical weight of level n; B_λ, blackbody emission intensity at wavelength λ; k_λ^∂, coefficient of absorption in a line at wavelength λ; $I_{\lambda otl}$, intensity of emission of an optically thin layer; I_λ^∂, intensity of emission in a line; Φ_{cap}; diameter of capillary; t, time, μsec.

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