INVESTIGATION OF A LOW-TEMPERATURE CESIUM PLASMA IN A LOW-VOLTAGE ARC

M. A. Lebedev

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The electron temperature T_e and electron concentration n_e in a cesium plasma in a low-voltage arc have been measured at an electrode temperature of 700°C using the double probe method. The distribution of T_e and n_e in the interelectrode gap d = 9.8 mm is obtained in the investigated range of pressures, P = $= 5.7 \cdot 10^{-3}$-$5 \cdot 10^{-1}$ mm Hg. The distribution $n_e = f(x)$ has a maximum near the cathode. T_e and n_e are obtained as a function of the discharge current I_p = 1-3 a, and a qualitative description of the burning mechanism for a low-voltage arc is given.

The behavior of a low-temperature cesium plasma is currently of great interest in connection with its use in thermionic and MHD devices for the direct conversion of thermal energy into electricity.

One of the most interesting manifestations of such a plasma is the low-voltage arc. A thermionic converter operating in the diffusion regime at some cathode temperature (of the order of 1300-1400°C), which depends upon the cesium pressure and the length of the interelectrode gap, spontaneously goes over into the low-voltage arc regime. The latter is the most promising operating regime for the converter.

The low-voltage arc in inert gases and mercury vapor is already familiar [1]. In 1951, Medices observed a low-voltage arc during thermionic conversion of thermal energy into electricity in a xenon atmosphere [2]. One of the fundamental problems in investigating the low-voltage arc is accounting for the burning mechanism, particularly when the burning potential is lower than the first excitation potential of the gas in which the arc burns.

In order to understand the burning mechanism of the low-voltage arc one must know the parameters of the gas discharge plasma and their distribution in the interelectrode gap. A very satisfactory qualitative explanation of the burning mechanism, based on the experimental fact of the existence of a maximum in the plasma potential and density distributions in the interelectrode gap near the cathode, has been given by Druyvesteyn [3].

Steinberg [4] and N. D. Morgulis [5], investigating low-voltage arc plasma parameters in cesium vapor by the single probe method, did not detect plasma density and potential maxima in the interelectrode space.

This article is concerned with a study of the distribution of electron temperature T_e and electron concentration n_e in a low-voltage arc (LVA) along the axis of the interelectrode gap and the effect on T_e and n_e of a cesium vapor pressure of $5 \cdot 10^{-3}$ to $5 \cdot 10^{-1}$ mm Hg and a discharge current in the range 1-3 a.

1. To measure the electron temperature and electron concentration in the cesium plasma of a low-voltage arc, the double probe method was used. The theory of the volt-ampere characteristic of a double probe has been treated by Jones and Malter [6] and Biberman and Panin [7].

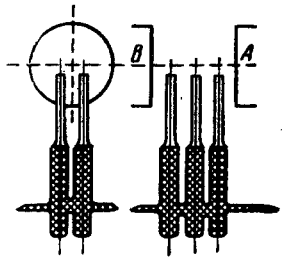

Fig. 1

The use of a double probe to obtain information about a cesium plasma has some advantages over the single probe method. To begin with, in cesium vapor the work function of the electrodes of the discharge chamber and the probe depends upon their material, their temperature, and the cesium vapor pressure. The probe temperature may change as it is moved along the interelectrode gap and in recording the probe characteristic. As the probe temperature changes, so does its work function. Thus, for a single probe, the contact potential difference between probe and electrode will change during recording of the probe characteristic and distort it. In the case of a double probe, both electrodes (probes) are subject to the same conditions and the contact potential difference between them is zero.

Moreover, the single probe is electrically coupled with one of the electrodes of the discharge chamber and, at a current of a few amperes across the discharge gap, the discharge is readily transferred to the probe. To prevent this, it is necessary to record the probe characteristics using a pulse circuit with a short probe signal and a small duty factor. The double probe is a floating system, not electrically coupled with the main electrodes; therefore, the possibility of the discharge being transferred to the probe is eliminated.

In the present study we used the discharge chamber with indirectly heated planar electrodes described in detail in

[8]. The working surfaces of the electrodes are the end faces of cylindrical stainless-steel shells 18 mm in diameter, which are sealed, using kovar rings, into a glass envelope from opposite sides. In the interelectrode gap, 9.8 mm long, there are three fixed double probes located as shown in Fig. 1. These probes are made of tungstein wire 0.2 mm in diameter, effective length 3.5 mm. Molybdenum glass capillaries are used as insulation. The electrodes of each double probe were located in a plane parallel to the surface of the main discharge chamber electrodes. The probes were spaced in the interelectrode space at distances of 0.7, 4.2, and 8.4 mm from electrode A and 1.4, 5.6, and 9.1 mm from electrode B. This distribution of the probes made it possible to record the probe characteristics at six points in the interelectrode gap by reversing the discharge polarity.

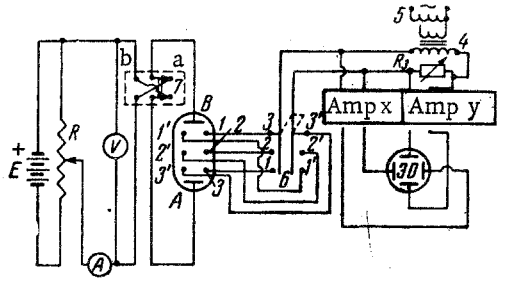

Fig. 2

The distance between the double probe electrodes must be much greater than twice the thickness of the perturbed layer near the probe (which is of the order of the Debye radius), so that the potential of one probe does not affect the other. In our conditions, the Debye radius D was of the order of 10^{-4} cm and the distance between probe electrodes $d_0 = 3 \cdot 10^{-1}$ cm, i.e., $d_0 \gg 2D$.

The collecting surfaces of the probes were identical, which ensured symmetry of the volt-ampere characteristic. This was checked by recording the probe characteristic at various points.

In the basic measurements, the probe characteristics were obtained on an oscillograph screen and photographed. The corresponding circuit is shown in Fig. 2. The 50-cps potential difference is fed from the secondary winding of transformer 4 between the double probe electrodes. This same potential difference, which is regulated by autotransformer 5, is passed through an amplifier to the horizontal deflection plates of the oscillograph. A small ohmic resistance R_3 is introduced into the probe circuit. The potential drop across this resistance, which is proportional to the probe current, is fed through an amplifier to the vertical deflection plates of the oscillograph. In this case the volt-ampere characteristic of the double probe is obtained on the oscillograph screen to the usual scale. A typical oscillogram of the probe characteristic is shown in Fig. 3.

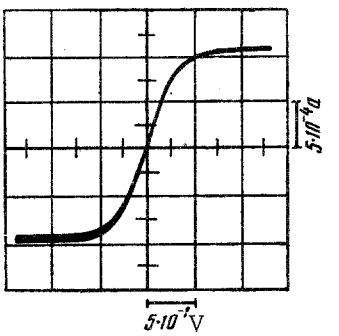

Fig. 3

The measuring circuit is switched from one probe to the other by means of switch 6. The discharge polarity is reversed by means of switch 7.

2. In the above-described experimental discharge chamber, using the double probe method, we measured the electron temperature and electron concentration in the low-temperature cesium plasma of a low-voltage arc. The cathode temperature T_k and anode temperature T_a were constant in all the experiments: $T_k = T_a = 700°C$.

Distributions of electron temperature T_e, in °K, in the interelectrode gap, x mm, at a constant discharge current $I_p = 1.0$ a are given in Fig. 4, where curves 1, 2, 3 correspond to pressures $p = 5.7 \cdot 10^{-3}$, $2.3 \cdot 10^{-2}$, $5 \cdot 10^{-1}$ mm Hg. It is clear from Fig. 4 that T_e has a maximum near the cathode and then drops quite slowly in the direction of the anode. The drop in T_e from cathode to anode is 25-30%. There is an explanation for this behavior of the electron temperature distribution in the interelectrode gap. Electrons emitted by the cathode are heated at an accelerating potential jump near the cathode, whose width is of the order of the Debye radius. Subsequently, energy is consumed between cathode and anode in inelastic collisions with atoms and in overcoming the decelerating electric field, if the potential distribution has a maximum in the interelectrode space. With increase in pressure, the electron temperature distribution is displaced almost uniformly into the region of lower values of T_e.

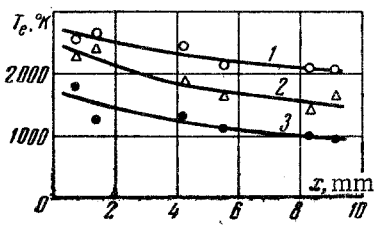

Fig. 4

In Fig. 5 the electron temperature T_e, 10^{-3} °K, and electron concentration n_e, cm^{-3}, are shown as functions of increasing cesium vapor pressure p, mm Hg, for $I_p = 1.0$ a at the point $x = 1.4$ mm (x is the distance from the cathode); the same figure also shows the burning potential V necessary for maintaining the discharge current at 1.0 a as a function of the cesium vapor pressure. With increase in pressure, the burning potential drops sharply, reaching a minimum at $p = 0.55$ mm Hg, after which it slowly increases. Since the burning potential directly affects the magnitude of the cathode potential jump, at which the electrons are heated, the relationship $T_e = f(p)$ displays similar behavior. At $p < 0.15$ mm Hg, the electron temperature rapidly decreases with increase in pressure, as is clear from Fig. 5; at $p > 0.15$ mm Hg, T_e depends only slightly upon the pressure.

The effect of the discharge current on the distribution of electron temperature T_e in the interelectrode space is illustrated in Fig. 6, where curves 1, 2, 3 correspond to currents $I_p = 1, 2, 3$ a. At low cesium pressures ($p = 2.3 \cdot 10^{-2}$ mm Hg, Fig. 6a) an increase in discharge current from 1.0 to 2.0 a leads to an increase in the electron temperature

near the cathode (x = 0.7 mm) from 2400 to 3650°K, i.e., by a factor of 1.5. With increase in cesium pressure, the relative increase in T_e for the same increase in discharge current decreases. Thus, for example, at $p = 5.5 \cdot 10^{-2}$ mm Hg, the electron temperature increases by a factor of 1.3 (Fig. 6b); at p = 0.5 mm Hg, T_e remains constant as I_p increases from 1.0 to 3.0 a (Fig. 6c).

The distribution of electron concentration n_e, cm^{-3}, in the interelectrode space at different values of the cesium pressure and constant discharge current $I_p = 1.0$ a is given in Fig. 7, where curves 1-5 correspond to pressures $P = 2.3 \cdot 10^{-2}$, $5.5 \cdot 10^{-2}$, $1.5 \cdot 10^{-1}$, $3 \cdot 10^{-1}$, and $5 \cdot 10^{-1}$ mm Hg. At all values of the cesium vapor pressure, the electron concentration has a clearly defined maximum at a distance of the order of 2 mm from the cathode. Over the interval $4 \leqslant x \leqslant 9$ mm, the concentration remains almost constant, i.e., $dn_e/dx \approx 0$. The anode concentration was determined from the current density at the anode. With increase in cesium pressure, the distribution $n_e = f(x)$ is displaced in the direction of a decrease in concentration.

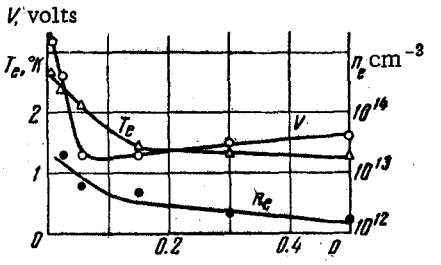

Fig. 5

The dependence of n_e upon cesium pressure at a distance x = 1.4 mm from the cathode is shown in Fig. 5 for I_p = = 1.5 a. As is clear from the figure, n_e decreases monotonically with increase in p. In this case the degree of ionization decreases strongly: from $n_e/n_a = 10^{-1}$ at $p = 2.3 \cdot 10^{-2}$ mm Hg to 10^{-4} at $p = 5 \cdot 10^{-1}$ mm Hg, where n_a is the volume concentration of neutral cesium atoms.

Figure 8a gives the distribution $n_e = f(x)$ for different values of the discharge current (I_p = 1, 2, 3 a) at a pressure $p = 5.5 \cdot 10^{-2}$ mm Hg, while Fig. 8b gives this distribution for $p = 5 \cdot 10^{-1}$ mm Hg. With increase in I_p the electron concentration increases throughout the interelectrode space.

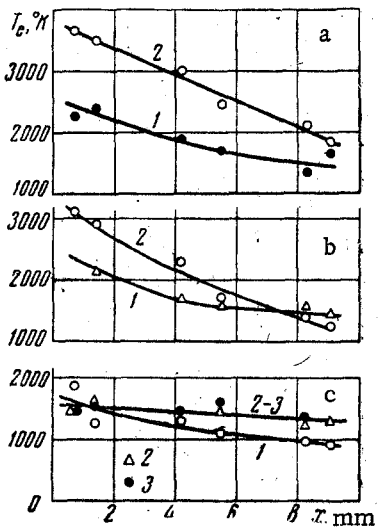

Fig. 6

The curve obtained for the distribution $n_e = f(x)$ with a maximum near the cathode agrees with the data of other authors [1, 3, 8, 9]. In [4, 5] a maximum of n_e was not observed, evidently because the minimum distance between probe and cathode was 5-6 mm. As our results show, the maximum of n_e is observed at a distance of the order of 2 mm from the cathode, while at x > 4 mm the electron concentration varies only slightly. The results of [5] (curve 3'), obtained for the same conditions as curve 3, are plotted in Fig. 8b. As is clear from the figure, the agreement is good.

3. Analysis of the experimental data from a study of plasma parameters and their distribution in the interelectrode space permit the assumption that ionization in a low-voltage arc is mainly from exicted levels, i.e., takes place in steps owing to the "tail" of the maxwellian distribution.

Electrons emitted by the cathode become maxwellian after passing through the accelerating cathode potential drop in the space-charge layer (cathode potential drop), which is less than the ionization potential, and form a heated electron gas with temperature T_e separated from the cathode surface by a barrier potential.

As calculations show, ionization due to the "tail" of the maxwellian distribution from the ground state at $T_e \leqslant$ $\leqslant$4000°K (observed under our conditions) is insufficient to sustain a cesium plasma [4].

The lifetime of the excited atoms is of the order of 10^{-8} sec, which is comparable with the collision time $\tau = 10^{-8}$-10^{-9} sec and, consequently, the probability of stepwise ionization should be low. However, it is necessary to take into account the imprisoned resonance radiation effect in cesium plasma, since the absorption probability for the resonance lines of atomic cesium is very high. Since it makes no difference what atom is excited, the transfer of a photon from one atom to another gives the effect of an increase in the lifetime of the excited state. According to Holstein's data [10], the above-mentioned effect increases the effective lifetime of an excited plasma atom in the pressure range 0.01-1.0 mm Hg by a factor of more than 10^3.

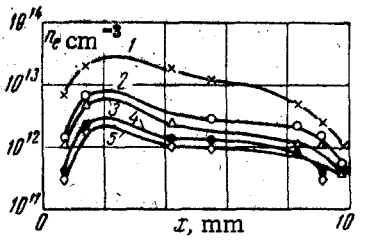

Fig. 7

Moreover, as shown by B. N. Klyarfel'd [11], the probability of ionization may be at least an order greater for atoms in the excited state than in the ground state.

These facts significantly increase the probability of stepwise ionization.

An estimate based on our data also shows that ionization from excited levels predominates.

A region of strong ionization is found near the cathode; this is confirmed by the presence of a maximum in the potential distribution. The region of the positive potential maximum is a potential well for the slow electrons formed during the ionization process. As a result of interactions with fast electrons and excited atoms, some of the slow electrons acquire enough energy to overcome the decelerating field and reach the anode. However, a great many escape from the potential well as a result of ambipolar diffusion to the walls of the discharge chamber and recombine there [12].

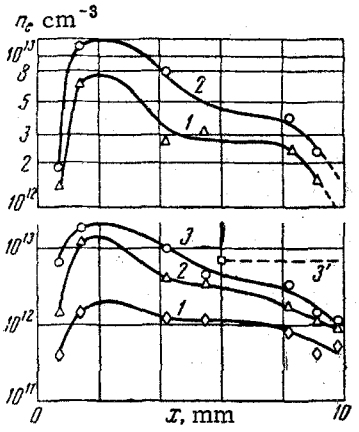

Fig. 8

When a low-voltage arc burns in cesium vapor, the discharge current exceeds by one or two orders the cathode emission current corresponding to the values of T_k and φ_k (φ_k is the cathode work function) before the arc is formed. Since it is impossible to attribute this to the production of current carriers in the chamber, for in a low-voltage arc $I_i / I_e = \sqrt{m / M}$ (I_i and I_e are, respectively, the ion and electron currents, m and M the electron and ion masses), the anomalous Schottky effect and field emission may be responsible. However, the most important role will evidently be played by a third mechanism: lowering of the cathode work function upon formation of a low-voltage arc. In the low-voltage arc a positive potential jump is observed at the cathode. Ions produced in the chamber travel to the cathode. Ions formed at the cathode surface as a result of surface ionization are returned by the jump to the cathode. Thus, a coating of ionized atoms is formed at the cathode, exceeding the equilibrium value corresponding to the cathode temperature and cesium vapor pressure. This leads to a lowering of the work function. However, a reduction in φ of 0.2 V is sufficient for the emission current to increase by one order of magnitude.

In conclusion, the author wishes to express his appreciation to V. N. Glazanov for his continuous interest in the work and I. P. Stakhanov and I. I. Kasikov for their useful comments.

REFERENCES

1. K. T. Compton and C. Eckart, "The diffusion of electrons against an electric field in the nonoscillatory abnormal low-voltage arc," Phys. Rev., vol. 25, p. 139, 1925.

2. G. Medices and G. Wehner, "Noble gas hot-cathode diodes with negative arc drop," J. Appl. Phys., vol. 22, p. 1389, 1951.

3. M. G. Druyvesteyn, "Der Neidervoltbogen," Z. Physik, vol. 64, p. 781, 1930.

4. R. K. Steinberg, "Hot-cathode arcs in cesium vapor," J. Appl. Phys., vol. 21, p. 1028, 1950.

5. N. D. Morgulis and P. M. Marchuk, "Physical effects associated with an arc-discharge cathode operating in cesium vapor," Ukr. fiz. zh., vol. 1, p. 59, 1956.

6. E. O. Jones and L. Malter, "Floating double probe method for measurements in gas discharges," Phys. Rev., vol. 80, p. 58, 1950.

7. L. Biberman and B. Panin, "Measuring the parameters of high-frequency electrodeless discharge using two probes," Zh. tekhn. fiz., vol. 21, no. 12, 1951.

8. Yu. K. Gus'kov, M. A. Lebedev, and I. P. Stakhanov, "Low-voltage arc in cesium vapor," Zh. tekhn. fiz., vol. 34, no. 8, 1964.

9. W. Stenzel and M. Bernstein, Low Temperature Cesium Plasma Converter, Advanced Energy Conversion, vol. 2, p. 499, Pergamon Press, 1952.

10. D. Alpert, A. O. McCoubrey, and T. Holstein, "Imprisonment of resonance radiation in mercury vapor," Phys. Rev., vol. 76, p. 1257, 1949.

11. B. N. Klyarfel'd, "Ionization in a positive column," DAN SSSR, vol. 24, p. 250, 1939.

12. Yu. K. Gus'kov, M. A. Lebedev, and I. P. Stakhanov, "The effect of a longitudinal magnetic field on a low-temperature arc," Izv. AN SSSR, ser. fiz., vol. 28, no. 9, 1964.

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