ON THE NATURE OF BEAD LIGHTNING

PHYSICS

1969

SovietRxiv

Abstract

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UDC 537.523.4

PHYSICS

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ON THE NATURE OF BEAD LIGHTNING

(Presented by Academician M. A. Lavrent' ev, 26 II 1969)

Bead lightning is a stable glow of a discharge channel that lasts for different times in different sections. The existence of such local regions is confirmed by time-resolved photographs of thunderstorm discharges ([1]). According to eyewitness observations, these regions—beads—take on a spherical form with approximately equal distances between the luminous formations ([2]-[4]) and with a lifetime of up to 2.5 sec. From time-resolved photographs of lightning it can be established that long-lasting localized afterglows arise during multiple discharges, and not during the first, strongest one, but during subsequent, often weak, discharges. It is characteristic that the brightness of this kind of afterglow reaches a maximum some time after the passage of the discharge. The duration of the localized afterglows depends substantially on the light-gathering power of the apparatus used, which indicates the low brightness of the phenomenon ([5]). This optical phenomenon has been considered by many authors in connection with bends of the main lightning channel and has been interpreted as an optical effect associated with the fact that observation of the region of bending is made from the end of the channel, so that a greater length of ionized gas lies along the line of sight. However, as was shown by photographing a spark discharge from two mutually perpendicular directions ([6]), the effect of localized afterglows does not depend on, and is not explained by, such a hypothesis. The aim of the present work was an experimental study of the nature of the localized afterglow.

The experiments were carried out on an installation consisting of a pulse transformer, to the primary winding of which (2 turns) a capacitor bank was discharged. Rod electrodes were connected to the secondary winding of the transformer (200 turns), between which the spark discharge under study was produced. The capacitance of the capacitor bank was varied from 10 to 40 μF, and the voltage from 8 to 30 kV; in this case the length of the spark gap varied from 17 to 50 cm. Experiments at reduced pressure and with various gases were carried out in an organic-glass chamber of dimensions $20 \times 20 \times 50$ cm^3.

The maximum current in the discharge did not exceed 1 kA, while the total duration of the damped oscillations of the current stage was no more than 380 μsec. The phenomenon was recorded with photoregistrators and a high-speed "Pantazet 16" cine camera at a filming rate of 3000 frames/sec. The brightness of

Fig. 1

Figure 1: Fig. 1

the afterglow was studied by means of an FEU-31 photomultiplier, onto whose cathode the light flux from the greater part of the spark gap was directed, excluding the near-electrode regions.

It was established that, in agreement with (^{6}), discharges in inert gases practically have no afterglow, whereas discharges in air, nitrogen, and carbon dioxide possess a very long afterglow. In discharges in air, after the arc stage the brightness of the channel glow often decreases, and then increases again and after several milliseconds reaches a maximum, which also occurs in thunderstorm discharges. This flaring-up of the afterglow is most often observed at high energies of the capacitor bank ($U = 10$ kV, $C = 40$ μF, Fig. 1). Cinematography of the phenomenon showed that the plasma cord, after the end of the current in the discharge, begins to lose stability. At atmospheric pressure an instability of the “snake” type arises predominantly (Fig. 2a). This instability most often—

arose at the parameters $U = 8 \div 10$ kV, $C = 24$ μF, and a spark-gap length $L = 17.5$ cm. At reduced pressure, $0.2 \div 0.3$ atm, a “sausage” instability arose predominantly (Fig. 2b). In individual cases, bead-like formations appeared along part of the plasma cord, and in one case the entire channel formed a peculiar “chain”(Fig. 2e). Apparently, this “chain”is a rare case of the occurrence of an instability of a higher order. In technical gases, such as nitrogen, carbon dioxide, and oxygen, instabilities of the plasma cord were also observed.

Fig. 1

It is significant that in all cases, when the energy of the capacitor bank was varied over wide limits, the ratio of the radius of the discharge channel a to the periodicity step λ changed only slightly.

As the energy of the capacitors was increased, turbulent motions began to be superposed on the periodic structure of the channel, and at $C = 40$ μF, $U = 30$ kV, $L = 30$ cm, the decaying channel was strongly turbulized, so that the probability of appearance of a periodic structure over the entire cine frame was sharply reduced (Fig. 2c).

Filming was also carried out of the decay of the spark channel in Töpler’ s setup. It was found that the space around the spark channel, approximately to a distance of several centimeters, is chaotically turbulized, and individual regions undergo convective motions with velocities of the order of 1 m/sec. This is probably due to buoyant forces arising as a result of heating of the air layers during absorption of the ultraviolet radiation of the spark. Experiments on focusing the shock wave formed at breakdown, and on the action of this wave on the discharge channel, showed that there is no connection between the occurrence of instability and gas-dynamic flows behind the shock-wave front.

Fig. 2

Figure 2: Fig. 2

The experimental results can be described sufficiently well if one assumes the existence of forces of the surface-tension type at the plasma boundary. It can be shown that a necessary condition for the occurrence of forces of this kind is the formation, at the boundary of the plasma cord, of a double electric layer. The energy required to maintain the double layer and the long afterglow can accumulate over comparatively long time intervals during passage of the discharge owing to the formation of "active nitrogen" (see, for example, (^{9})). In this case, for describing the phenomenon one may adopt the hydrodynamic model of the decay of a cylindrical jet of liquid flowing into another medium and having a surface tension relative to this medium.

As a result of solving problem (^{7}), the increment of growth of perturbations α is found as a function of the surface tension σ of the liquid jet relative to the medium, the velocity of inflow of the jet into the medium V, the density of the jet ρ and of the medium ρ_0, the radius of the unperturbed jet a, and the dimensionless wave number $m = 2\pi a/\lambda$. For $V = 0$ and axisymmetric oscillations ($S = 0$),

$$\alpha^2 = \frac{\sigma}{a^3\rho} m(1-m^2)\frac{I_1(m)}{I_0(m)} = \frac{\sigma}{a^3\rho} Y(m), \tag{1}$$

where $I_0(m)$ and $I_1(m)$ are modified Bessel functions. It follows from formula (1) that growth of perturbations ($\alpha > 0$) is possible only for $0 < m < 1$. The functions $Y(m)$ and α attain their maximum value at $m = 0.7$, and the growth of perturbations at this value of m is most probable. Consequently, putting $m = 0.7$ in (1) and substituting the value $Y(0.7) = 0.12$, one can, having determined from experiment $\alpha = \tau^{-1}$, where τ is the const-

Fig. 2

···of the growth rate of the disturbances, to compute σ. For $V \geqslant 0$ and arbitrary deformations ($s = 0, 1, 2, ...$), the problem was approximately solved in [8]:

$$\alpha^2 = \frac{\rho_0 V^2 m^4 \ln(m/2)}{2\rho a^2} + \frac{\sigma}{2\rho a^3} m^2(1 - s^2 - m^2). \tag{2}$$

It follows from (2) that, for $V = 0$, $\alpha > 0$ only if $s = 0$, i.e., only axisymmetric perturbations can grow. Instabilities with $s = 1, 2, ...$ are possible only when $V \geq V^* > 0$, i.e., when the velocity of motion at the liquid surface is not less than a certain value. For $V \geq V^*$, as the number s increases, α decreases, i.e., in any case the growth of instability of the lower modes is most probable. For $V \gg V^*$, α does not depend on s, and all modes have an equal probability of arising, which leads to atomization of the jet. The most probable value in this case is $m = 0.8$, and for very viscous liquids $m \to 1$ (^{8}).

When the air pressure is lowered, absorption of the optical radiation energy of the spark occurs in a larger volume of air and at a lower velocity of convective motion ($V \approx 0$), and $s = 0$, which agrees with experiment. When the pressure is increased and the energy is increased, the velocity of the convective flows increases ($V > V^*$), and growth of modes with $s \geq 1$ becomes possible. Finally, at very high energies ($V \gg V^*$) there occurs random fragmentation of the "jet" —turbulization of the discharge channel.

The only discrepancy consists in the preferential occurrence of the mode $s = 1$ in the experiment; this discrepancy is apparently explained by the fact that, in the computational model, the jet flows into a stationary liquid, whereas under experimental conditions the surrounding medium is strongly turbulized, which should lead to forced pumping of the perturbation of the mode $s = 1$.

From the calculations, the most probable value of m for real liquids lies within $0.7 \leq m \leq 1$, i.e., the most probable step of the periodicity λ is bounded by the relation $6a \leq \lambda \leq 9a$. For bead lightning, according to the data of (^{1}) and the observations of Tepler (^{2}), $6a \leq \lambda \leq 15a$.

From our experiments, $7a \leq \lambda \leq 14a$. The adopted model makes it possible to estimate σ from the experiment. For our conditions $a = 0.1 \div 0.2$ cm, $V^* \sim 1$ m/sec, $\alpha \sim 3 \cdot 10^4$ sec^{-1}. Hence $\sigma = 1 \div 8$ dyn/cm.

It can be shown that, for surface-tension forces $\sigma \geq 1$ dyn/cm to arise at the plasma boundary, it is necessary that the condition $\varphi^2 l^{-1} \geq 3 \cdot 10^6$, or $n^{2/3} \geq 7 \cdot 10^{-17}$, be fulfilled, where φ is the effective potential difference of the double layer in volts, l is the characteristic thickness of the double layer in centimeters, and n is the concentration of negatively charged particles on the outer "plate" of the layer in cm^{-3}.

Thus, the disintegration of the discharge channel in air occurs with loss of stability; moreover, a maximum in the brightness of the afterglow is observed $4 \div 7$ msec after the cessation of the current in the discharge under the conditions indicated in the text.

The loss of stability can be explained by the presence of surface tension at the boundary of the plasma column. In this case the formation of stable configurations close to spherical is possible.

To obtain formations of the bead- or ball-lightning type, certain conditions must be fulfilled, namely: repeated heating of a limited volume in order to accumulate chemical energy of the gas. In this case the forces arising because of turbulization of the surrounding medium must be smaller than the surface-tension forces.

The authors are deeply grateful to Acad. M. A. Lavrent' ev for his constant attention to the work.

Received
17 II 1969

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Note: Figure translations are in progress. See original paper for figures.