MILLISECOND CINEHOLOGRAPHY OF COLLECTIVE OPTICAL DISCHARGES

Yu.N. Zakharov and Yu.M. Sorokin

Gorky State University
Received August 9, 1988

The 4-sequence multiplex hologram scheme for recording collective optical discharges (COD) is realized which uses independent, optical sources and electronic delay lines which can operate over a wide range of time intervals. The effect of COD propagation through an aerosol medium has been recorded for the first time. This effect is of an intermittent ("relay-race") type. It is shown that under "relay-race" conditions the COD lifetime increases due to the delay of the evolution of the secondary discharge nuclei with respect to the primary one. Temperature and electron concentration profiles in the discharge are restored using an original algorithm based on the threshold model of COD.

INTRODUCTION

Collective optical discharge (COD) in a dry aerodispersed medium at atmospheric pressure is a rather well studied phenomenon. A threshold model of COD consistent with the measured values of breakdown thresholds[2,4,5] is constructed. The dynamics of an isolated microtorch as well as the the dynamics of an ensemble of interacting microtorches at different stages of discharge was investigated in both numerical[6–8] and laboratory[4,9–14] experiments. As follows from the available experimental data, COD, in its development, repeats only the main regularities of its evolution and is not reproduceable in detail. For this reason it is impossible to restore the dynamics of the process using the data of different samplings. In order to solve this problem it is necessary, on the one hand, to record the sequence of the instantaneous state of the object at all stages of the evolution of the discharge, and, on the other hand, it is necessary to restore the COD spatial characteristics with a given accuracy over the entire period of its existence.

But the interpretation of the spatial profiles of the main physical parameters of COD's has been carried out until now only by uging the shadow method with diaphragms placed off focus[10,12,14]. Basically, this method is a gradient method and is good enough for revealing the fronts but is rather bad for revealing the structure of the discharge core. In order to obtain more information about the dence and highly ionized COD cores (in comparison with simple interferometry[11]), one can make use of the possibilities offered by optical cineholographic methods, which sire highly informative, have good accuracy and are noise protected. But the known cineholographic schemes[15–17] do not embrace the time range necessary for a successful description of such an object with a rather long life such as a COD.

In cineholography usually only one radiation source is used. For the formation of a series of frames one can use either optical delay lines, which simultaneously carry out (under monopulse conditions) the function of spatial separation of the position of recording of the individual frames[15] or scanning in the recording plane to separate the images obtained by a series of pulsed[16,17].

In the first case one can manage to bring the time interval between the expositions up to several tens of nanoseconds while in the second case the time intervals achieved range from 25 μs to 1 ms. In this case limitations on the recording speed which exist for small delays are determined by the presence of mechanical shifts. The devices used now for holographic cinematograph work at frame repetition frequencies up to 20 Hz, i.e. the interval between successive frames is 50 μs. Thus for presently available holographic systems the time intervals between the recordings of 1 μs to 50 μs are inaccessible.

Several images, recorded on the same hologram and representing a series of the states of the object, form a multiplex (composed) cinehologram. The possibility of rapid recording of different images constitutes the advantage of such holograms (in comparison with traditional cinematographic systems which require change of the photomaterial) because the smallness of the mechanical shifts between recordings, even their complete absence, depending on the means of multiplexing, allows one to remove the limitations on the speed of operation connected with the requirements of the mechanical stability of the recorder.

In practice it is possible to extend arbitrarily the time range by using several single-type sources of sounding radiation in the same holographic scheme. Results of the study of COD core structure and dynamics by means of such a scheme covering the whole interval during which highly ionized plasma exists are presented in this paper.

EXPERIMENTAL TECHNIQUE

A block diagram of the experimental setup used is shown in Fig. 1. Four ruby lasers of the same type (1–4) with their own resonators and passive

Q-switches are used as the light sources. The storage capacitors of these lasers are charged simultaneously and whole triggering pulses are applied to the flash lamps in the delays formed using electronic generators, which makes it possible to achieve the desired time intervals between the pulses (6, 7, $\Delta t_1 - \Delta t_n$ in Fig. 1). In our scheme the time intervals between exposures can be changed from several μs up to several milliseconds, which is quite enough for recording all the main stages of the COD development.

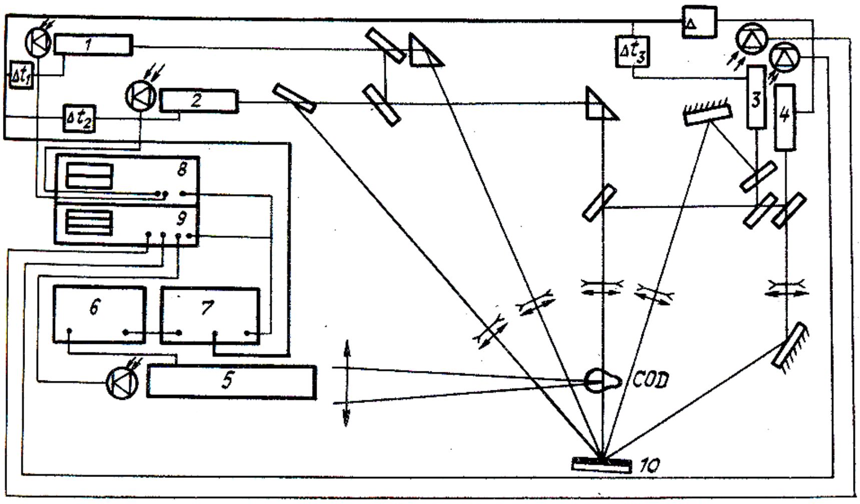

FIG. 1. Blockdiagram of the setup for recording multiplex COD-holograms using independent laser sources.

The time delays can be varied, if necessary, from nanoseconds up to tens of seconds by changing the delay ciruitry.

The instability of the time delays connected with the use of passive Q-switching does not stand in the way of the solution of the above-stated problem. But if the requirements on the accuracy of the time-gating are more strict (as is, the case e.g., in studies of a long laser spark structure), it is necessary to use active Q-switching in laser sources. It is advisable to construct the optical scheme of the setup in such a way that it does not contain any components which must be moved in the course of the exposing operations, thus not imposing any limitations from below on the time between exposures. For this purpose, part of the radiation from each source is directed to one and the same collimator and form four reference beams crossing the subject beam at different angles. Since the hologram 10 is formed by four pairs of beams, all four subholograms contribute to the image restoration process when illuminated by a restoring wave coincident with one of the reference waves. As a consequence, these four images can overlap, thus spoiling the quality of the restored image. The possibility of obtaining independently restored images of individual frames in the main cinehologram, formed using reference waves directed at an object from different angles, can be provided by proper geometrical arrangement of the optical scheme of the cinehologram recording. The required characteristics of such an arrangement can be easily calculated. Calculations show that at a large enough distance from the hologram the restored images do not overlap due to their angular separation. For the same reason the axial background noise also does not interfere.

In our cineholographic setup the angles at which the reference beams are incident on the hologram are as follows: for the object beam $\alpha = 19°$; for the reference beams $\beta_1 = -17°$; $\beta_2 = -36°$; $\beta_3 = -6°$; $\beta_4 = 32°$. Diffraction angles of the restored real images are as follows: $\alpha_1^* = 65.5°$; $\alpha_2^* = 90°$; $\alpha_3^* = 32.3°$; $\alpha_4^* = -47.2°$. The imaginary image is restored in the direction of propagation of the object beam. As a result, the possibility exists of independently restoring the image of any frame using the appropriate beam and also of obtaining mutually interfered images of any two (or more) frames when illuminating the hologram with two (or more) reference beams simultaneously.

The initiating laser 5 is synchronized with the cineholographic setup and a recording oscilloscopes[8,9].

A COD was obtained in laboratory air containing aerosols at the focal point of a lens illuminated with the beam from a neodymium glass laser 5. The laser delivered pulses of about 1 μs (is total duration in the free generation mode. The averaged intensity at the focal spot of 2 to 6 μm in diameter reached values of 5×10^5 to 10^6 W/cm^2.

Aerosol powder of boron carbide B_4C was blown through the focal volume by an aerosol generator[10]. The generator provides stationarity of the statistical characteristics of the aerosol ensemble (concentration $n_a = 10^3$ cm^{-3} and average size of particles $a = 100$ μm) within a stream of about 1 cm in diameter. As a result, the region where the aerosol stream and the focal volume overlap (with mutually perpendicular axes and close transverse sizes) and where the core of the COD is formed turns out to be compact and close to spherical. Thus one can obtain an idea of the dynamics of COD expansion along different directions even if the diameters of the object and reference beams are limited. Sounding pulses of duration τ_{p2} = 40 ns were delivered by a Q-switched ruby laser at the wavelength 694 nm. The time delays $\Delta t_1 - \Delta t_4$ were chosen so as to allow the recording of the most essential stages of the COD evolution.

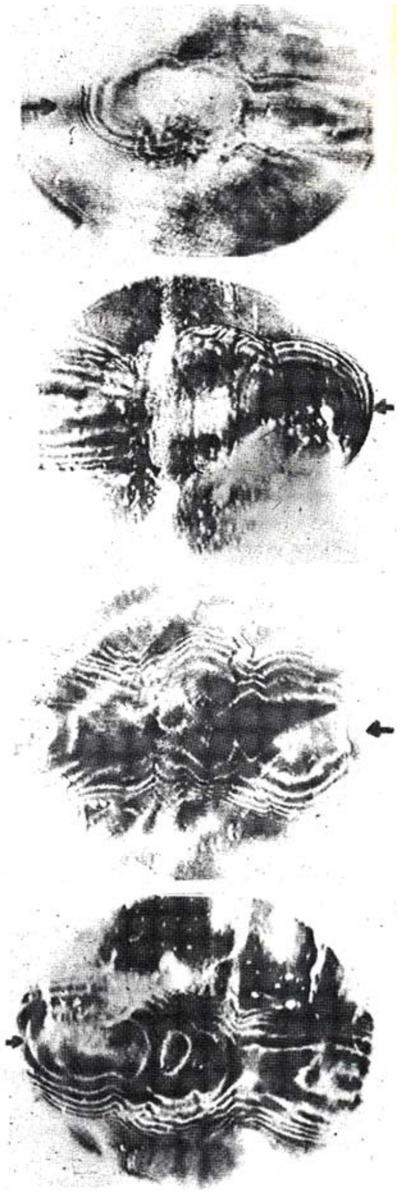

FIG. 2. Restored holographic interferograms of COD at successive moments: a) 400 μs; b) 810 μs; c) 1040 μs; and d) 1360 μs. The axis of aerosol stream is in the plane z = 0 and coincides with the vertical axis of the field of view. The arrows show the direction of propagation of the initiating beam. A is the primary COD-core, and B is the secondary COD-core.

QUALITATIVE RESULTS

Restored holograms for one of the COD realizations are presented in Fig. 2. Figure 2a visualizes the stage of the formation of the COD-core during the process of confluence of the microtorches produced on individual aerosol particles. The characteristic "tail" of the discharge is mainly due to a photoreactive aerosol ejection along the beam (cf Ref. 3) and to processes of interaction of the system of the vapor tracks of the particles with the optical radiation (influence of the track aureole on the propagation of microwave radiation is discussed in Ref. 18).

Figure 2 illustrates a new mechanism of expansion of the collective optical discharge formed in the aerosol medium. Indeed one can see from Fig. 2a in comparison with Fig. 2b that the primary COD-core (Fig. 2a) which is formed by a time $t \geq 400$ μs can under certain conditions produce a secondary COD-core in parallel with the well known process of continuous heat-conductive expansion near its leading front, which becomes a new center of heat-conductive expansion of the discharge (Fig. 2b). Formation and development of the secondary COD-core are delayed with respect to the primary core so that the discharge dynamics takes on a discrete "relay-race" character. Thus, in Fig. 2b the primary COD-core is larger than the secondary one, but in Fig. 2c both of them are already of the same size, while in Fig. 2d the secondary core becomes the primary one. The characteristic rate of the COD-core expansion according to Fig. 2 is about 15 m/s ($v \approx 15$ m/s), which is agrees with the slow heat-conductive mechanism mentioned above. This value should be taken as an estimate of the "relay-race" expansion velocity under the nearthreshold conditions of COD.

Anisotropy of the "relay-race" (expansion along the counter direction to beam propagation) and also the conditions under which it exists are caused by the peculiarities of the physical conditions surrounding COD. As it was first shown in the Ref. 19, the most efficient mechanism of collective optical breakdown is the two-stage one, in which at the first stage separate plasmoids appear on the clusters (microensembles) of aerosol particles with locally increased concentration (anomalous, superthreshold concentration, according to Refs. 2 and 3). In this case the formation of the COD-region takes place at the second stage due to the plasmoids joining. The plasmoids are sustained in this process by the vapors from the vaporizing aerosol of nominal (average, subthreshold) concentration.

The "relay-race" is essentially a variant of the same process . The primary COD-core plays the role of one of the plasmoids of the aerosol microensemble. The microensemble initially isolated from the plasmoid with nearthreshold (in the sense defined in Refs. 2 and 3) parameters can produce a lagging plasmoid or a system of them, turning then into a secondary COD-core if pumped with vapors from the background aerosol and with heat from the primary COD-core. It is clear that the probability of occurence threshold conditions is highest when the aerosol microensembles are located along the beam, which explains the anisotropy of the "relay-race" expansion of COD towards the beam. In the direction along the beam the "relay-race" is suppressed by the photoreactive ejection of those aerosol particles having velocities greater than the heat-conductive velocity.

The mechanism of COD expansion discussed here explains the increase of the total lifetime of the discharge. This increase can be seen from comparison of the time intervals assotiated with Fig. 2 with the data in Ref. 14, where it was found using the results of shadow diagnostics, that the process of relaxation begins already at times $t \sim 0.5$ ms. Similar conclusions can be drawn from a comparison of Fig. 3 and Fig. 4 which depict the results obtained using COD-holograms for different realizations. In the case represented by the data in Fig. 3 the process of COD-expansion is observed more distinctly.

RESTORATION OF THE COD-PHYSICAL PARAMETERS

Holographic interferograms of COD obtained experimentally (see Fig. 2) even under conditions of cylidrical symmetry of the object in the working plane do not yet allow yet the restoration of the profiles of the COD-physical parameters in the image space.

To obtain a unique solution of this problem, some additional assumptions based on knowledge of some physical characteristics of the development of the object are necessary. The simplest assumption is used in the Ref. 10. It is based on the slow heat-conductive mechanism of COD formation and can be reduced to isobarity of the object at all stages of its development under the condition of local thermodynamic equilibrium (LTE). The validity of the assumption of the existence of LTE conditions in COD is confirmed by data obtained using syncronous shadow diagnostics at the two wavelengths[12]. To elucidate the spatial structure of the pressure field and to estimate its value in the COD with due regard for the molecular component, the authors of Ref. 14 have used a rather artificial division of the COD into two regions in one of which (internal) the aerosol component is supposed to be fully ionized while in the other one (external) the neutral component is supposed to make the main contribution to the phase shifts.

The quantitative threshold model of COD developed at present[2,3] enables one to put forward another, physically more natural and spatially uniform algorithm of restoration of profiles of such COD physical characteristics temperature and electron number density under conditions of LTE. This algorithm can be used even in the case of so-called "cold agglomeration"[1]. The basic assumption used to interpret this mechanism is that under near threshold conditions the temperature, at which the agglomeration of the microtorches takes place is close to the boiling temperature T_b of the aerosol substance. This assumption is insufficient to restore the pressure profile, but it is sufficient to estimate its value supposing only instantaneous isobarity of the COD-core. The cineholograms were processed according to this latter algorithm was used for the cineholograms processing. In this case the temperature $T = T_b$ was taken at the boundary ofthe COD-core. The results are given in Figs. 3 and4. Here the dashed lines show the temperature level of the microtorch agglomerations ($T = T_b \sim 4{\times}10^3$ K).

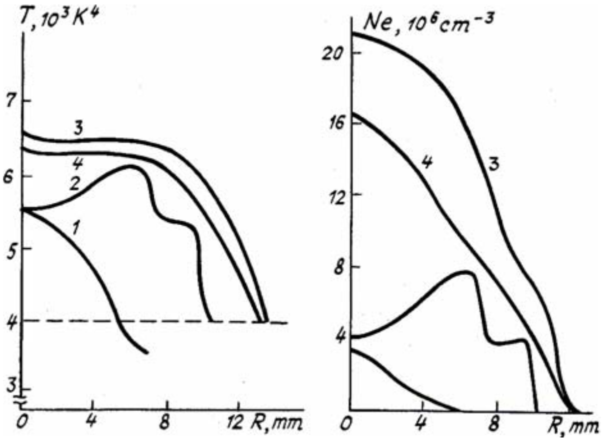

FIG. 3. Profiles of the physical parameters of COD corresponding to the cineholograms in Fig. 2.

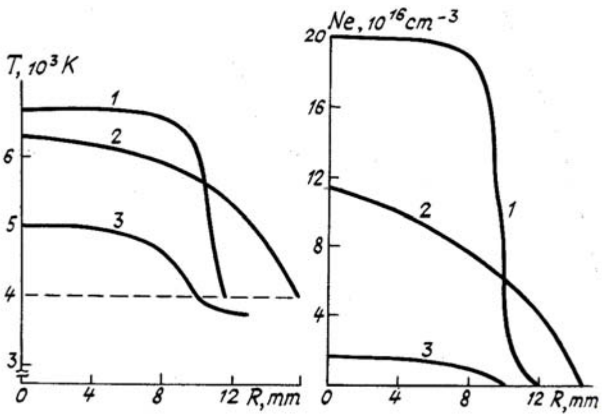

FIG. 4. Profiles of the physical parameters of COD in the absence of the "relay-race" mechanism of the discharge expansion at successive moments: 1 — 440 μs; 2 — 800 μs; 3 — 1200 μs.

Figure 3 depicts the successive profiles of temperature and electron number density along the axis of the aerosol stream in the presence of the "relay-race" mechanism of COD-expansion (see interferograms in Fig. 2). In Fig. 4 the profiles of the same physical parameters are restored approximately at the same moments of the realization at which the "relay-race" mechanism is absent.

For the realization corresponding to Figs. 2 and 3 the following estimates of the pressure in the COD-core were obtained at the successive moments: $P_1 = 6{,}5$ atm; $P_2 = 8$ atm; $P_3 = 9$ atm;

P_4 = 11 atm. These values are in good agreement with the shadow diagnostic data in Ref. 14 and with the numerical modeling results in Ref. 8. The quantitative differences between the temperature behavior of the COD represented in Figs. 3 and 4 and those in the Ref. 14 (where the maximum temperature is higher than 10^4 K) are quite natural. They are due to the fact that in this paper, as mentioned above, the nearthreshold for the COD regime of "cold agglomeration" is studied while in Ref. 14 the COD-dynamics is studied under essentially superthreshold threshold.

CONCLUSIONS

To study the spatial structure and dynamics of long-lived plasmoids like COD-region it is advisable to record multiplex holograms without mechanical shifts of the photomaterial using several independent sources working in succession (the "mitral lies" principle).

Under certain conditions the COD-expansion in an aerosol can have a "relay-race" character of successively emerging charge cores, which leads to an increase in the lifetime of the entire plasma region.

The correct use of the threshold COD-model allows one to construct and apply a quite simple but efficient algorithm for the restoration of the spatial profiles of the temperature and electron number density as well as to provide an estimate of the pressure in the discharge.

REFERENCES

1. Yu.M. Sorokin, Zhurnal Technicheskoi Fiziki **56**, 1431 (1986).
2. Yu.M. Sorokin, I.Ya. Korolev, and E.M. Krikunova, Kvantovaya Elektronika **13**, 2464 (1986).
3. Yu.M. Sorokin, Optika Atmosfery **1**, No. 8, 36 (1988).
4. V.A. Vdovin, S.V. Zakharchenko, A.M. Skripkin, and Yu.M. Sorokin, in: Proceedings of the Institute of Experimental Meteorology (*Trudy Instituta Eksperimentalnoi' Meteorologii*), (Gidrometeoizdat, Moscow, 1981).
5. S.V. Zakharchenko and Yu.M. Sorokin, ibid., p. 82.
6. V.A. Vdovin and Yu.M. Sorokin, Zhurnal Technicheskoi Fiziki, **51**, 1449 (1981).
7. V.A. Vdovin and Yu.M. Sorokin, Izvestiya Vuzov, Radiofizika, **26**, 1220 (1983).
8. I.Ya. Korolev, T.P. Kosoburd, V.A. Vdovin and Yu.M. Sorokin, Zhurnal Technicheskoi Fiziki, **57**, 2314, (1987).
9. S.V. Zakharchenko, S.M. Kolomiets, and A.M. Skripkin, Pis'ma v Zh. Tekh. Fiz., **3**, 1339 (1977).
10. I.Ya. Korolev, T.P. Kosoburd, E.M. Krikunova, and Yu.M. Sorokin, Zhurnal Technicheskoi Fiziki **53**, 1547 (1983).
11. S.V. Zakharchenko and A.M. Skripkin, in: Proceedings of the Institute of Experimental Meteorology (*Trudy Instituta Eksperimentalnoi Meteorologii*), (Gidrometeoizdat, Moscow, 1983).
12. Yu.N. Zakharov, T.P. Kosoburd, and Yu.M. Sorokin, Zhurnal Technicheskoi Fiziki **54**, 969 (1984).
13. S.V.Zakharchenko, L.P.Semenov and A.V.Skripkin, Kvantovaya Elektronika **11**, 2487 (1984).
14. T.P. Kosoburd and Yu.M. Sorokin Zhurnal Technicheskoi Fiziki **58**, 1318 (1988).
15. Yu.I. Ostrovskii, M.M. Butusov, and G.V. Ostrovskaya, Holographical Interference [in Russian], (Nauka, Moscow, 1977).
16. B.R. Hilderbrand and K.A. Haines, J. Opt. Soc. Amer. **57**, No. 2, 155 (1967).
17. Yu.N. Zakharov and S.N. Mensov, Zhurnal Technicheskoi Fiziki **52**, 992 (1982).
18. I.Ya. Korolev, Yu.M. Sorokin, and S.E. Finkel'shtein, Radfiotechnika i Electronika **33**, 360 (1988).
19. V.A. Vdovin, Yu.N. Zakharov and Yu.M. Sorokin., in: Fourth All-Union Symposium on Laser Bean Propagation through Dispersive Media, Obninsk–Barnaul, 2, 141 (1988)