March 2, 2023 0:14 1st draft
Technical Physics, 2022, Vol. 67, No. 2

03

Influence of external electric field on optical breakdown in high-speed flow

© *V.N. Zudov,*[1] *A.V. Tupikin*[2]

[1] Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch, Russian Academy of Sciences,
630090 Novosibirsk, Russia
[2] Kutateladze Institute of Thermophysics, Siberian Branch, Russian Academy of Sciences,
630090 Novosibirsk, Russia
e-mail: zudov@itam.nsc.ru

Received August 25, 2021
Revised October 6, 2021
Accepted October 8, 2021

The influence of an electric field on the plasma of an optical discharge in subsonic and supersonic air flows has been studied experimentally. The presence of a weak electric field practically does not affect the size of the plasma formation, but, regardless of the configuration of the field lines and the polarity of the applied voltage, it leads to a decrease in the probability of optical breakdown. The experiment has shown that the plasma created by focused laser radiation is very sensitive to the presence of an electric field. When a voltage exceeding 22 kV was applied to the ring electrodes, powerful quasi-stationary streamers were formed in the flow. The presence of an optical discharge plasma made it possible to create an electric discharge in fields with an intensity below the breakdown threshold of the medium. The effect of quenching and the processes of development of an optical discharge were studied depending on the speed and characteristics of the electric field. Quenching of the optical discharge was observed when a voltage of 22 kV and higher was applied. Despite the preservation of the geometric dimensions of the optical discharge, the high-temperature region in the flow can be increased by using electric streamers. This leads to an increase in the energy supplied to the flow, and thus allows combustion to be initiated and flame stabilized at higher flow rates.

Keywords: experimental modeling, laser radiation, optical breakdown, electric field, electric discharge, sub- and supersonic air flow.

DOI: 10.21883/TP.2022.02.52943.244-21

Introduction

When intensive laser radiation is focused in the atmosphere, air is ionized due to multiphoton or tunnel ionization, one or several low-conductivity plasma channels originate [1]. The peculiarities of laser beam filamentation, such as propagation to large distances [2,3] and breakdown in the air [4], have given rise to many potential technological and scientific applications. Laser plasma was used as a source of terahertz and X-ray radiation for spectroscopic and medical applications [5]. Sensitive methods have been developed for measuring the ultraviolet radiation using optical gas breakdown [6,7].

Implementation of combined optical and electric discharges is also applied in various scientific fields. For instance, in [8–13] the combination of an electric field with laser-induced breakdown was applied for generation of a laser trigger switch of a spark arrester. The developed device layout is based on reduction of the discharge breakdown voltage by generating plasma of laser-induced breakdown in the interelectrode space [8]. It should be noted that the streamer length considerably increases in the creation of a laser-induced electric breakdown [14]. This can be used to reduce the threshold characteristics of ignition and combustion of a highly flammable mixture [12]. Optical discharge plasma in [13] was generated in low-pressure air (~ 20 Torr) with focusing of CO_2-laser radiation, where it was demonstrated that plasma generated due to laser-induced breakdown can be suppressed by an external electric field. It should be noted that optical breakdown without electric field application has been implemented regularly (with almost 100-% probability). Optical breakdown in an electric field with intensity above 600 V/cm was to a great extent suppressed (the breakdown frequency decreased). Further increase of electric field intensity improved the conditions of optical discharge implementation (breakdown frequency increased) up to the initial state. This indicates the presence of an extremum for the electric field parameters when an optical discharge is implemented in it.

The optical breakdown mechanism for laser radiation with quantum energy below the medium ionization potential is related to development of an electron avalanche [1]. In the absence of external fields, the process accountable for electron losses in the beam focusing region is diffusion that can be significant at low pressures. The application of an external field increases the electron outflow, thus increasing the radiation threshold intensity at an optical breakdown. An additional mechanism for origination of free electrons exists above a certain value of electric field intensity; such a mechanism provides a higher speed of development of a laser breakdown region. This is probably the reason of the presence of an extremum for the electric field parameters when an optical discharge is implemented in it.

A change in the breakdown threshold by superimposition of an electric field onto the focusing region of the Nd:YAG laser (wavelength of 1064 nm) in the nanosecond time scale was demonstrated in [14] (at atmospheric pressure). Thereat, the radiation threshold intensity at breakdown of the medium increased all the time, without reaching the extremum depending on intensity of the external electric field. A similar result was obtained in [15], where the application of an external electric field to the focus volume of a high-pressure gas cell caused only an increase in the radiation threshold intensity at an optical breakdown. The authors believe that this is due to electrostatic treatment of gas (from particles which are the breakdown centers) and due to removal of free electrons from the focusing region between laser pulses. The experiments with the laser radiation wavelength of $1.06\,\mu$m with the pulse duration 200 ps and interval of 7.5 ns have demonstrated that electrostatic treatment efficiently suppresses the optical breakdown at 20 atm and the maximum single pulse intensity of 140 J/cm^2 (~ 0.7 TW/cm^2). Thereat, the impact of an external electric field onto the focal volume creates an additional loss mechanism (drift) which helps reduce the free electron density below the threshold one required for optical breakdown initiation.

The authors of [14,15] did not observe any extremum of electric field intensity upon optical discharge implementation in it, possibly because such experiments were conducted at pressures considerably exceeding the pressure in [13]. It should be noted that the experimental dependence of laser radiation threshold intensity on medium pressure has an extremum upon an optical discharge in neon and argon, as shown in [11].

In this paper we have studied the impact of an external electric field on optical discharge plasma in a high-speed flow, at near-atmospheric static pressures. Plasma was exposed to a stationary electric field with intensity up to 24 kV/cm. Phenomena related to optical discharge decay have been observed. Special attention was paid to conditions at which it was impossible to create a combination of optical and electric discharges.

1. Experimental setup

Plasma of an optical pulsating discharge was generated using an electric-discharge CO_2-laser LOK-3SGU (developed by the Institute of Laser Physics of the Siberian Branch of RAS), which provided the pulse-intermittent operation mode with a pulse repetition rate up to 60 kHz, average power being approximately 1.0 kW. The shape of the incident radiation pulse was recorded by an IR photoreceiver FD-511-2 (spectral range up to $11\,\mu$m). Radiation of optical discharge plasma was recorded by the FD-256 photoreceiver, range of $0.4-1.1\,\mu$m. The laser in the

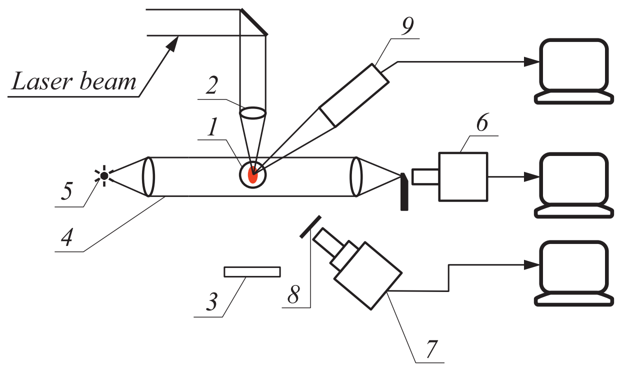

Figure 1. Experiment layout: *1* — object under observation; *2* — lenses; *3* — absorber; *4* — schlieren system; *5* — light source; *6* — photocamera; *7* — high-speed camera; *8* — interference filter; *9* — CCD-camera.

experiments operated in the batch mode (3–6 pulses) with a carrier frequency of 30–40 kHz, batch repetition rate was 5–7 kHz. CO_2-laser radiation propagated across the flow and was focused by a ZnSe lens between the electrodes on the jet axis at the given density from the nozzle exit, equal to 14 mm and varying insignificantly during the experiments. Lenses with a different focal distance ($f = 63, 95, 125$ mm) were used in the experiments. Fig. 1 shows the experiment layout.

Air was supplied into the prechamber and escaped from the supersonic nozzle into the flooded space (to the free atmosphere). The prechamber had the inner diameter of 80 mm, length of 95 mm. Flow was generated using a caprolon conical nozzle with an angular salient point. The diameters of the critical and outlet cross-sections are equal to 15.5 and 20 mm respectively. The distance between the said cross-sections was 25 mm. The maximum prechamber pressure was $P_0 = 0.8$ MPa at $T = 290$ K.

The gas-dynamic structure of the flow was determined using a shadow scheme with a slit and a flat knife. The lighting source was a spark discharge in argon with the glowing duration of $1\,\mu$s. Flow visualization by the shadow method allowed for reliable determination of the boundaries of the optical discharge zone in the flow, as well as spatial scales of heat discontinuities that moved downstream from the breakdown region.

Different electrode configurations were used in the experiments (Fig. 2): plane electrodes — an electric field along a laser beam (*a*); circular electrodes — a field along the flow and across the beam (*b*). A configuration with circular electrodes instead of plane plates was also tried out.

Fig. 2, *a* shows the layout for plane-parallel plates spaced at 3 cm, which were located beyond the impinging jet boundaries. The electrodes had holes 5 mm in diameter for passage of a laser beam focused on the air stream axis.

Fig. 2, *b* shows an experiment layout with a longitudinal (in the flow direction) electric field. An electric field was generated by two circular electrodes. Electrode voltage

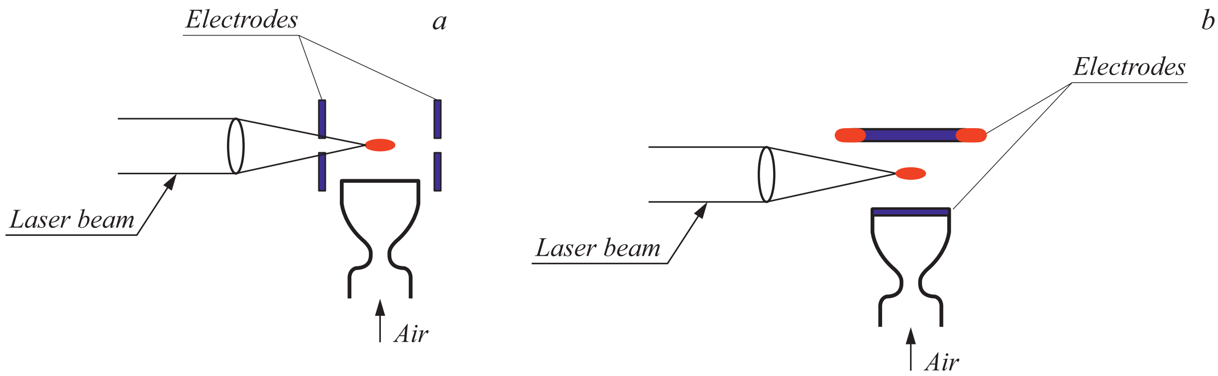

Figure 2. Layout of the electrodes and laser beam: *a* — electric field along the beam; *b* — field across the beam.

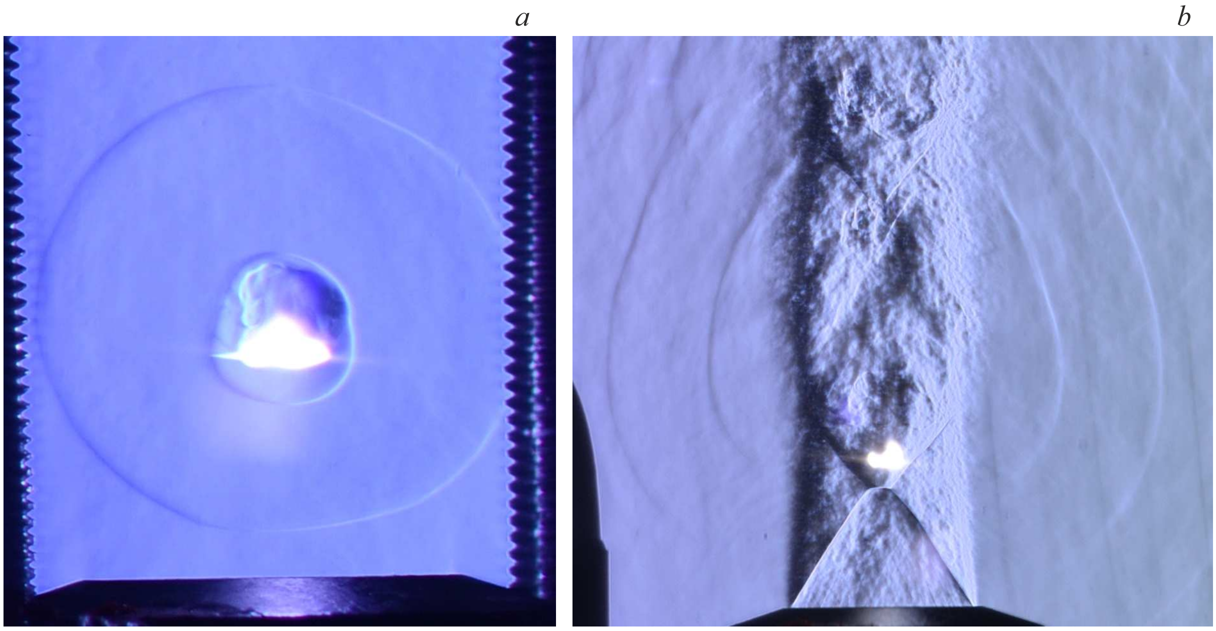

Figure 3. Shadow recording of an optical discharge when an electric field is absent: *a* — without a flow; *b* — in a supersonic flow ($P_0 = 0.66$ MPa).

varied from 6 to 30 kV. Polarity might change in the course of experiments.

Three power sources with voltages up to 2, up to 6 and up to 24 kV were used in the experiments. The first source was used to generate a weak electric field. The other two were used to determine the boundary of joint existence of the optical discharge and electric streamers. At first, the electrodes in the form of plane plates were used to generate an electric field across the air stream. The use of circular electrodes in the same scheme improved the conditions of electric discharge (streamer) generation.

2. Experimental results and discussion

Fig. 3 shows the images of shadow recording in case of an optical breakdown when an electric field is absent: *a* — in a stationary medium, *b* — in a supersonic jet. Fig. 3, *a* shows a well-visible shock wave propagating from the energy feed region across the stationary medium. The plasma region dimensions were 5−7 mm. The shock wave first repeats the plasma shape and then takes the shape of a circle. In Fig. 3, *b* we can see the structure of the supersonic jet in case of off-design outflow to the atmosphere, the laser beam focusing region is above the shock wave cone. The observed structure comprises a supersonic submerged jet with typical shock waves, a plasmoid, heat discontinuities in its wake. The space behind the jet boundary contains periodic sound disturbances with a frequency corresponding to the laser pulse repetition rate, Fig. 3, *b*.

Fig. 4 shows the structure of subsonic flow and an optical discharge with the use of plane electrodes for three cases: without an electric field (Fig. 4, *a*); with an electric field $U = 6$ kV, a positive electrode on the right (Fig. 4, *b*) and a positive electrode on the left (Fig. 4, *c*). It should be

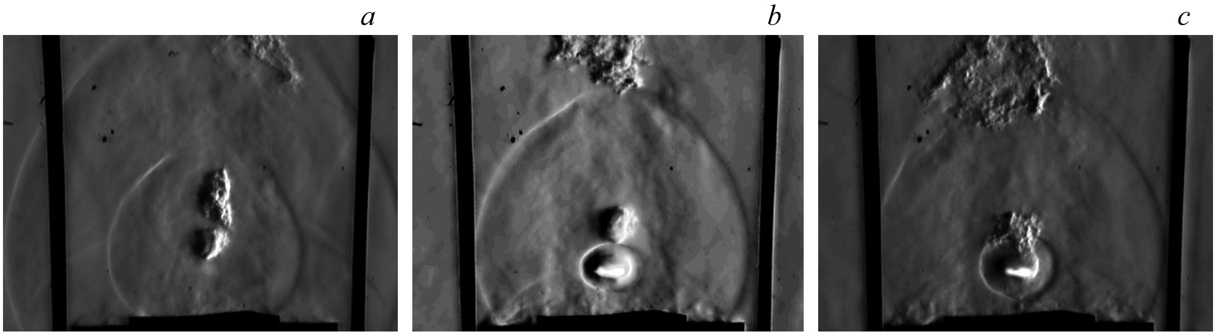

Figure 4. Shadow recording for the case with two plane electrodes in a subsonic flow: *a* — when an electric field is absent; *b* — field (6 kV) is directed from left to right; *c* — field is directed from right to left.

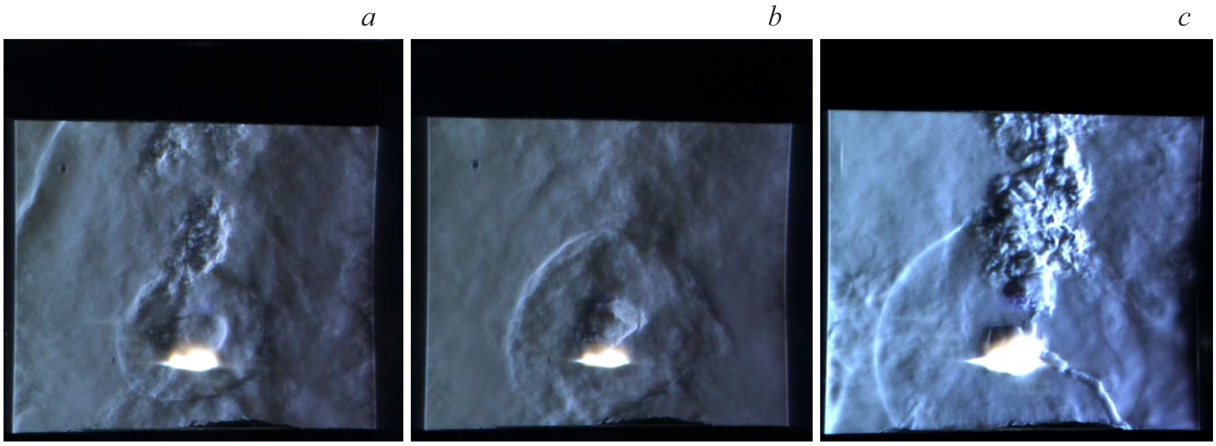

Figure 5. Shadow recording for the case of circular electrodes (the anode is above) in a subsonic flow: *a* — without an electric field ($\Delta p = 0.6$ atm); *b* — $U = 18.5$ kV ($\Delta p = 0.6$ atm); and *c* — $U = 18.5$ kV, $\Delta p = 0.016$ atm.

noted that the main elements of the flow structure in all cases do not differ greatly. Thereat, a limited plasma region forms in the flow, which is indicated by elliptically shaped shock waves. The plasma region dimensions are ~ 3 mm (focusing spot diameter being 0.2 mm), and a periodic heat wake is behind it. The wake structure depends on laser pulse repetition rate. The experiment was conducted at the laser pulse repetition rate of 32 kHz, while prechamber pressure was 0.18 atm higher than the atmospheric one. No significant impact of the electric field on the flow structure is observed.

The conditions of existence of an optical discharge deteriorated in a subsonic flow at a low electric field intensity irrespective of polarity (a decreased breakdown probability). It means there were fewer responses of the originating plasma of the optical discharge when an electric field was superimposed. This is probably due to electrostatic treatment of the focusing region from foreign particles, which are the breakdown development centers, and an increased electron outflow from the focusing region under the electric field impact.

A weak electric field (up to 11 kV) virtually does not affect the plasma dimensions, regardless of polarity. When voltages are high, a change in field polarity did not cause considerable changes in the plasma shape, and also its dimensions in case of streamer presence. The shape and limit characteristics of an electric breakdown in the experiments depended on electrode configuration, applied voltage and air stream speed.

Polarity change on the circular electrodes in the absence of an electric breakdown also does not give rise to significant changes in the flow structure (Fig. 5). An increase of field intensity in this electrode configuration has lead to the implementation of a combined optical and electric discharges. Fig. 5, *c* shows a well-visible streamer from the nozzle exit (anode) to the optical breakdown region, while no streamer channels are observed above the plasma, i.e. in the optical discharge wake.

In a separate set of experiments we have considered the impact of differential pressure (Δp) between the prechamber and the environment onto the generation of an optical discharge. The laser pulse repetition rate was $f = 32$ kHz. The studies were conducted in the range of differential pressure Δp from 0.016 to 0.6 atm. Circular electrodes were used to generate an external electric field. It has been established that at $\Delta p = 0.6$ atm only an optical discharge

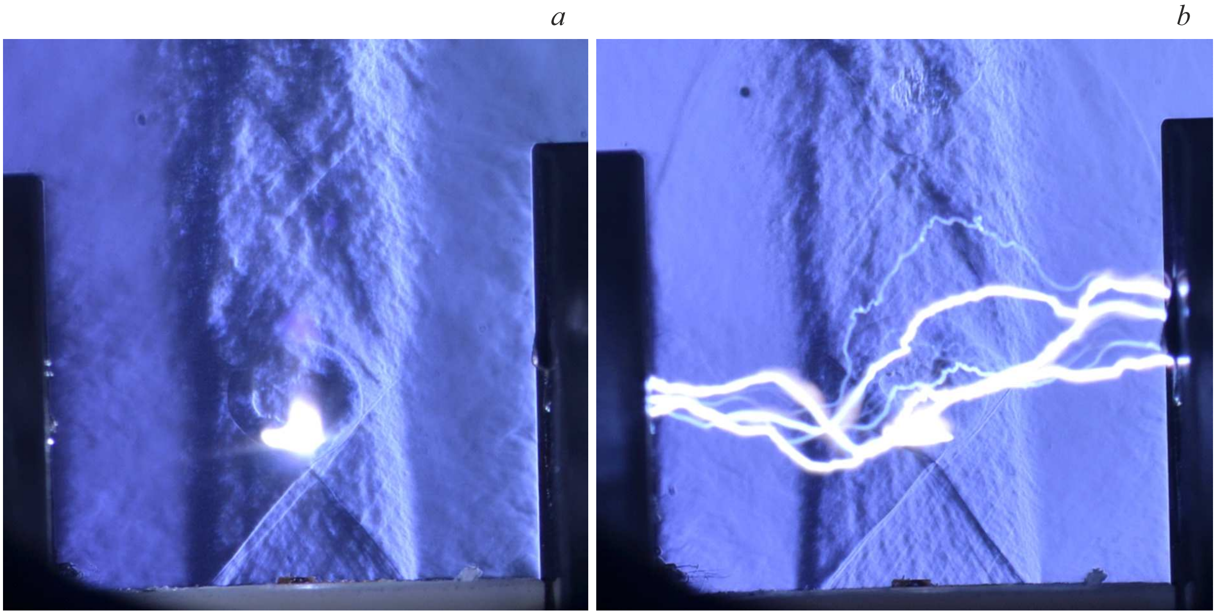

Figure 6. Optical discharge in a supersonic jet when an electric field is present (total pressure $P_0 = 0.5$ MPa, $U = 22$ kV): *a* — without streamers, *b* — with streamers.

was present (Fig. 5, *b*), while at $\Delta p = 0.016$ atm an electric breakdown took place in addition to the optical breakdown (Fig. 5, *c*). With the electrode voltage of 18.5 kV the current was 0.8 mA, voltage dropped to 17 kV and current decreased to 0.6 mA in case of an electric breakdown.

Different positions of the electric breakdown region in time are indicative of non-steady processes. There is a dependence of electric breakdown probability on pressure. It has been established that rare electric breakdowns occur at $\Delta p = 0.06$ atm, and they do not occur in the differential pressure range $\Delta p = 0.036{-}0.06$ atm.

The configuration where plane electrodes were replaced by circular electrodes has been also tried out. The air jet flowed into the flooded space at a supersonic speed (design Mach number $\mathrm{M} = 2$). The structure of a supersonic jet with an optical and a combined (optical plus electrical) discharge under the same outflow conditions is shown in Fig. 6. Thereat, two scenarios can be implemented: without electric discharge streamers and with an electric breakdown of the medium. The position and quantity of streamers can vary from experiment to experiment, emphasizing the stochasticity of streamer channel development. Electric discharge streamers generate additional heat liberation and a combined discharge can therefore create a heat input region that significantly exceeds the optical breakdown dimensions. The mode of existence of such plasma in and out of a jet are close to quasi-stationary conditions, which is required for initiation and stabilization of combustion in the high-speed flow of air-fuel mixture.

The optical discharge is quenched by the electric field in certain conditions. The optical discharge in a supersonic jet decayed at a gradual increase of electrode voltage from 11 to 22 kV (Fig. 7). This phenomenon did not depend on electric field configuration and was observed in the field located both in the flow direction and along the laser beam.

As an example, Fig. 7 shows the impact of increasing circular electrode voltage on intensity of glowing from the breakdown region. Glowing from a plasmoid gradually decreases as voltage increases. Quenching of an optical discharge by an electric field located in the flow direction also took place at subsonic outflow of the jet. This effect has been observed at other pressures as well ($P_0 = 0.4$ and 0.5 MPa). Due to a monotonous decrease of electric field intensity, the optical discharge recovers to its unperturbed state (without a field).

Thus, the parameters of an external electric field can be changed to control the plasma of an optical discharge, including its complete quenching by the field. The quenching effect is related to electron outflow from the laser radiation absorption region.

The above-mentioned quenching effects are confirmed by the recorded radiation of the optical discharge plasma. When a field was superimposed on the focusing region, there were fewer peaks on the oscilloscope trace of the plasma signal. Fig. 8 shows the results of incident radiation recording for a laser pulse (index *1*) and optical discharge plasma (index *2*). The left part of the figure gives the data without a field, and the right one gives signals after field activation. A regular plasma response is observed till time $\sim 900\,\mu$s, plasma radiation is not present after field activation. Most probably, electrostatic treatment of the focusing region from foreign particles, which are the breakdown development centers, takes place, i.e. a situation similar to the one described in [15] occurs. At that, the speed of electron outflow from the focusing region increases under the electric field impact.

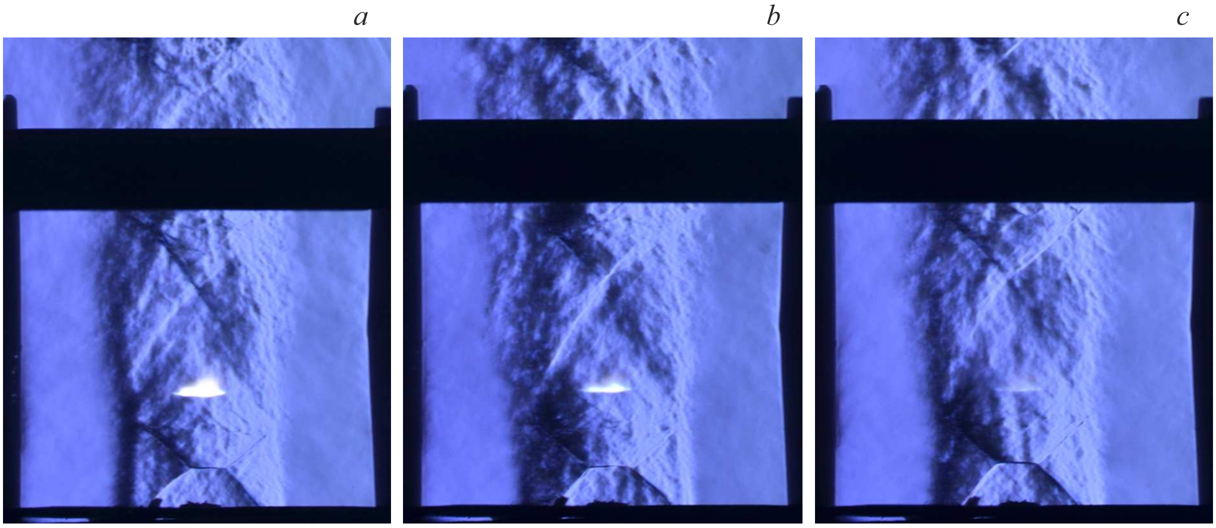

Figure 7. Quenching of optical discharge at an increase in electric field intensity (from left to right), the field being across the beam ($P_0 = 0.3$ MPa, $U = 11-22$ kV).

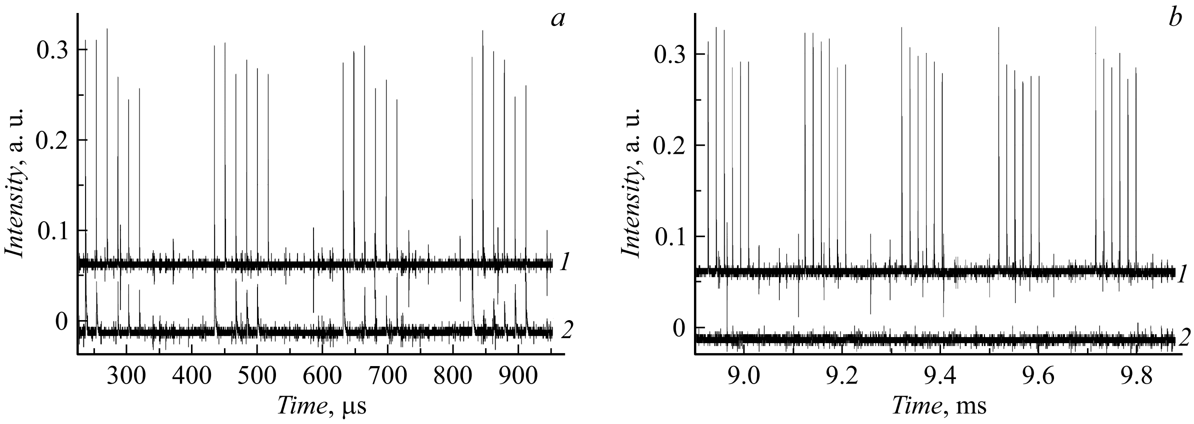

Figure 8. Photometric recording of radiation at quenching of an optical discharge.

Conclusion

A procedure for optical measurements has been developed and tried out for recording the flow structure during interaction of a supersonic flow with electric and optical discharges.

We have considered two modes of impact of an external electric field on the optical discharge plasma: an electric field is either in the air stream direction or across the air stream. Plane and circular electrodes were used.

The experiment has demonstrated the possibility of simultaneous existence of optical and electric discharges.

It has been shown that the parameters of an external electric field can be changed to control the plasma of an optical discharge, including its complete quenching.

Two modes of joint existence of the plasma of optical and electric discharges have been found. In the first condition, an electric discharge was between the optical discharge plasma and an electrode. In the second one, an electric discharge was between the electrodes and an optical discharge existed at the same time.

The effect due to joint implementation of an optical and an electric discharge in a flow will cause an additional energy impact on the flow structure, thus improving the conditions for initiation of fuel mixture combustion stabilization, approaching the quasi-stationary mode of energy impact on supersonic flow.

Funding

The work has been partially funded by the Russian Foundation for Basic Research (grant № 19-08-00304).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] Yu.P. Raizer. *Lazernaya iskra i rasprostraneniye razryadov* (Nauka, M., 1974) (in Russian)
[2] E.I. Asinovsky, L.M. Vasilyak, O.P. Nesterkin. TVT, **35** (6), 858 (1997) (in Russian).
[3] O.B. Danilychev, S.A. Tulsky. ZhTF, **48**, 2040 (1978) (in Russian).
[4] S.B. Leonov, A.A. Firsov, M.A. Shurupov, J.B. Michael, M.N. Shneider, R.B. Miles, N.A. Popov. Phys. Plasmas, 19, 123502 (2012). https://doi.org/10.1063/1.4769261
[5] A. Houard, Y. Liu, B. Prade, V.T. Tikhonchuk, A. Mysyrowicz. Phys Rev. Lett., **100**, 255006 (2008).
[6] D.W. Hahn, N. Omenetto. Appl. Spectrosc., **64**, 335A (2010).
[7] D.W. Hahn, N. Omenetto. **66**, 347 (2012).
[8] M.J. Kushner, R.D. Milroy, W.D. Kimura. J. Appl. Phys., **58**, 2988 (1985).
[9] T. Fujii, A. Zhidkov, M. Miki, K. Sugiyama, N. Goto, S. Eto, Y. Oishi, E. Hotta, K. Nemoto. Chinese J. Phys., **52**, 440 (2014). DOI: 10.6122/CJP.52.440
[10] V.Ya. Nikulin, S.P. Tsybin, A.E. Gurey. Kratkie soobshcheniya po fizike FIAN, **6**, 15 (2017) (in Russian).
[11] V. Kumar, R.K. Thareja. J. Appl. Phys., **64**, 5269 (1988).
[12] E. Takahashi, S. Sakamoto, O. Imamura, Y. Ohkuma, H. Yamasaki, H. Furutani, K. Akihama. J. Phys. D Appl. Phys., **52**, 485501 (2019).
[13] J. Tulip, H. Seguin. Appl. Phys. Lett., **23**, 135 (1973).
[14] E. Takahashi, S. Kato. OSA Continuum., **3**, 3030 (2020). DOI: 10.1364/OSAC.399530
[15] R.A. Mullen, J.N. Matossian. Opt. Lett., **15**, 601 (1990).