Cylindrical shock waves investigation, produced by pulse discharge

Igor Doroschenko, Igor Ivanov, Alexander Kuznetsov, Irina Mursenkova and Irina Znamenskaya*

Faculty of Physics, Lomonosov Moscow State University, Moscow, Russia
*corresponding author: znamen@phys.msu.ru

Abstract An experimental and CFD study is presented of the flow with shock waves from vertical plasma breakdown column 24 mm long. High specific energy input of pulse discharge with plasma electrodes in the discharge camera was evaluated trough comparison of CFD results and high-speed shadowgraphy. Cylindrical shock waves arising from the energy input based on the vertical breakdown were visualized. Flow evolution up to 3 ms after discharge was studied with high-speed shadowgraphy. Speed and intensity of shock waves were measured; also instability of hot post-discharge channel was visualized. A 2D numerical simulation of the initiation of shock-wave flows based on the Navier-Stokes equations was made. The model of pulse cylindrical energy deposition was used, based on experimental data. Solving the inverse problem shows that 20-22% of the energy of the volume discharge, stored in the capacitor is converted into energy of cylindrical shock waves - in the vertical breakdown channel. In the presence of low density area (vortex column) in gas flow the controlled breakdown (self-localization of the discharge plasma) occurs. Images of plasma glow localization in flow with vortexes were obtained.
Keywords: shock waves, high-speed shadowgraphy, CFD, combined nanosecond discharge

Introduction

Plasma flow control, based on the plasma actuation, is a novel active technique to improve flow characteristics [1]. The flow control method based on localized plasma generation is a logical development of the concept based on the application of organized energy input. Electric discharge action on low-speed gas flow is through heating, ionic wind. Discharge action on high-speed gas flow is through disturbances and shock waves generation, which can influence flow structure and parameters. The energy rate being released quickly into media is an important parameter of the plasma action on gas media. It can be calculated by solving inverse problem: the experimental images of shock waves produced by pulse discharge should be matched with CFD images of the process [2, 3]. In the present paper an experimental and CFD study is presented of the flow with shock waves from vertical plasma breakdown column 24 mm long. Cylindrical shock waves arising from the energy input based on the vertical breakdown were visualized. Energy input rate of pulse discharge with plasma electrodes in the discharge camera was evaluated trough comparison of CFD results and high-speed shadowgraphy.

Experimental setup

Experimental setup was a shock tube with the discharge chamber of special construction. It had been built for the purposes of studying the nonstationary processes of the interaction between the subsonic or supersonic gas flows and the spatial or surface short-pulsed electric discharge [2, 3]. The action of the discharge could be considered as instant from the gasdynamical point of view. The setup configuration is shown in Fig. 1. The discharge chamber was mounted with the shock tube's channel and it had the same rectangular profile of 24×48 mm2. The combined discharge pulse voltage was 25 kV. The discharge current had amplitude of ~1 kA and duration of ~200 ns. The length of the discharge volume was 10 cm. The top and bottom walls of the discharge volume were the plasma electrodes which produced the ultraviolet radiation for the preionization of the spatial discharge volume. This configuration of the discharge allowed improving the homogeneity of the main spatial discharge. The chamber's sidewalls were made of quartz glass to make the discharge glow and shock formations visible by optical means or by using the visualization technique. The combined glow images in the discharge chamber are presented in Fig. 2.

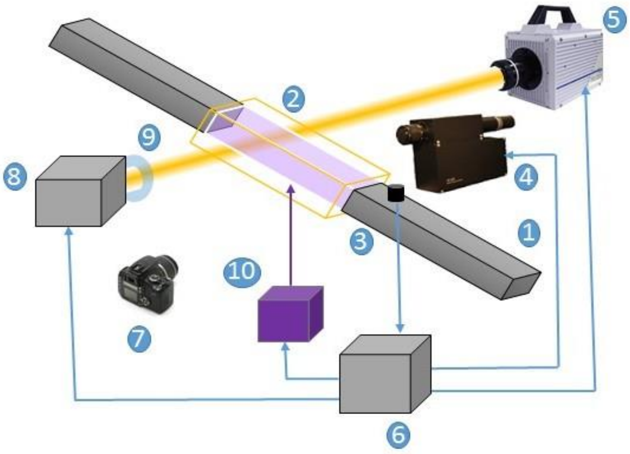


Fig. 1 Experimental setup: 1 - shock tube, 2 - discharge chamber, 3 - pressure gages, 4, 5 - high-speed cameras, 6 - delay generator, 7 - photo camera, 8 - light source , 9 - optics, 10 - spark-gap controller

The initial electric impulse leads to the development of sliding surface discharges of two plasma electrodes. Their ultraviolet glow produces a preionization of the spatial area. After 30 ns, the spatial discharge's current starts. After that, the spatial and sliding discharges simultaneously glow for 150–200 ns. The sliding surface discharge plasma electrode has a structure of parallel discharge channels on a dielectric surface. It was possible to record the integral images of discharge glow redistribution by photo camera. As can be seen from Fig. 2 a, if there is no flow in the discharge area, the plasma glow is quite homogeneous all over the discharge section. The phenomenon of discharge "self-localization" in front of the shock wave was observed for all the variety of shock wave positions in the discharge section [2].

If the gas pressure was more than 100 Torr, spatial discharge energy and discharge glow concentrates in the vertical cylindrical column – electric breakdown occurs (see Fig. 2 b, c). This regime is similar to the transition from the glow-like regime to spark regime for nanosecond pulsed discharges [4]. Glow discharge does not heat the gas by more than hundreds kelvins, which is consistent with the low level of conduction current. This is in contrast to spark regime, which heats the gas by several thousand kelvins, as discussed in [4]. An analysis was made of the spatial and temporal structure of the column plasma glow depending on the pressure (90-150 Torr). Increasing the pressure is followed by breakdown column changing. Fig. 3 presents visual column width thickness dependence on electric voltage.

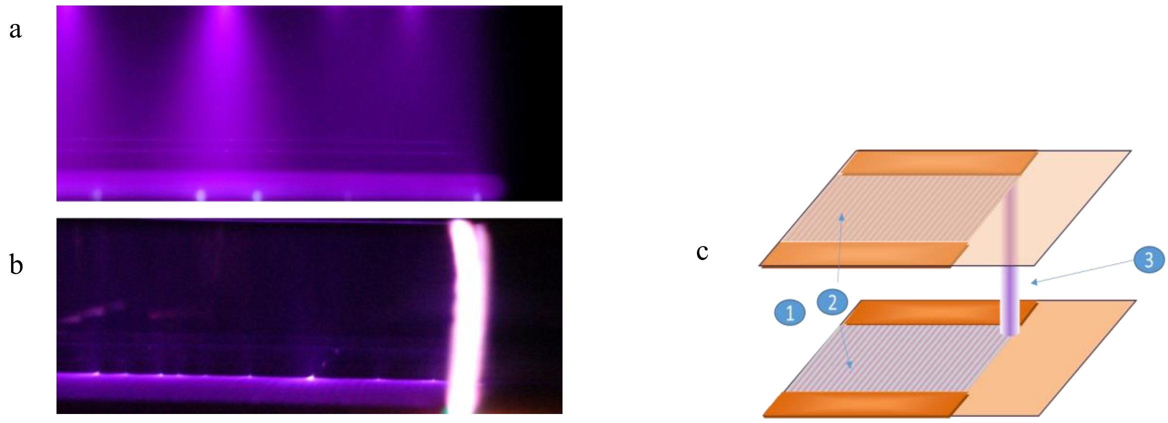


Fig. 2. Two regimes of combined discharge (a, b) and the scheme of plasma column formation (c). 1 - discharge volume, 2 - plasma sheets, 3 - contracted volume discharge (plasma column).

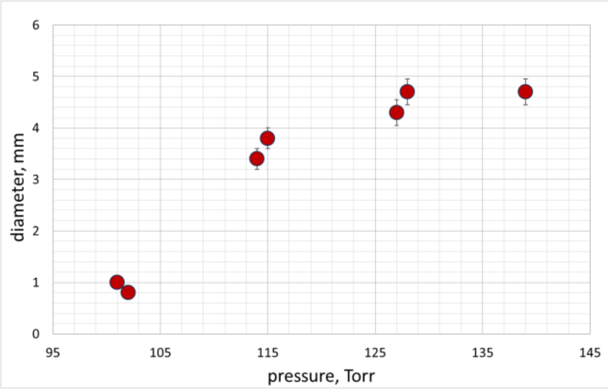
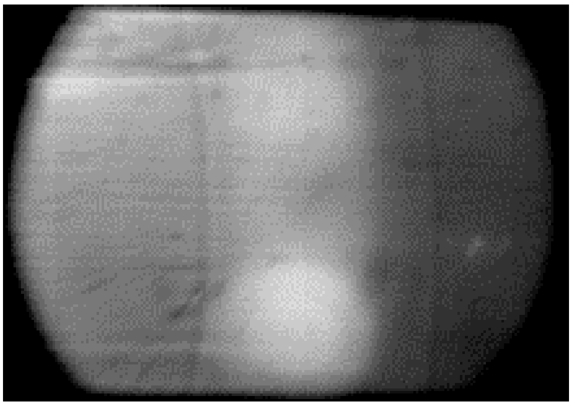
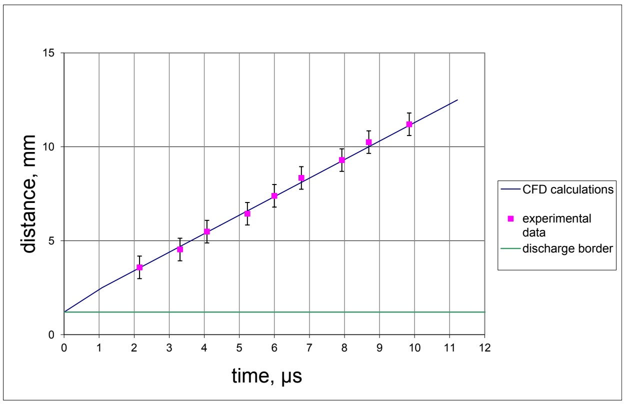


Fig. 3.

2 High-speed shadowgraphy

The gas flow caused by spatial discharge localization to cylindrical breakdown column was studied by high-speed shadowgraphy. The light source for shadowgraphy was the LED lighter with light pulse duration up to 5000 μs. High-speed shadow imaging of the flow that arises from the plasma column in air was conducted. The shooting speed of high-speed camera Photron wass 525000 frames/sec for full-scale image shadowgraphy (Fig.4a) and 1000000 frames/sec for narrow-scale image shadowgraphy (Fig.5). Flow evolution up to 5 ms after discharge pulse was studied. Instability of hot post-discharge channel was visualized. Cilindrical shock wave was the result of a fast energy release due to fast plasma thermalization. Fig. 4 a shows a full-scale shadow image of the cylindrical shock wave at a pressure of 120 Torr. It is 24 mm high. Positions (cylinder diameter) of shock wave were measured for time moments up to 20 μs after the discharge (Fig. 4 b).





a b

Fig. 4.

Fig. 5 presents 11 consequent images of the shock wave spreading in the narrow area in the central part of the discharge chamber. Images were obtained at regular serial intervals of 1.9 μs. Constricted volume discharge (plasma column) is visible on frames 1-3 from the top. The first frame clearly shows the plasma column. Intensity of plasma column glow is reducing on frames 2 and 3. The propagation of shock wave from the pulse plasma column is clearly visible. Later the shock wave interacts with the walls and relaxes.

In the presence of low density area in gas flow the controlled breakdown (self-localization of the discharge plasma) occurs. Images of plasma glow localization in flow with vortexes and with plane shock wave were obtained. Fig. 6 presents the image of combined discharge localization in the separation vortex zone behind the wedge in the flow after the shock wave: discharge energy is concentrated in the low density area organized in the flow.

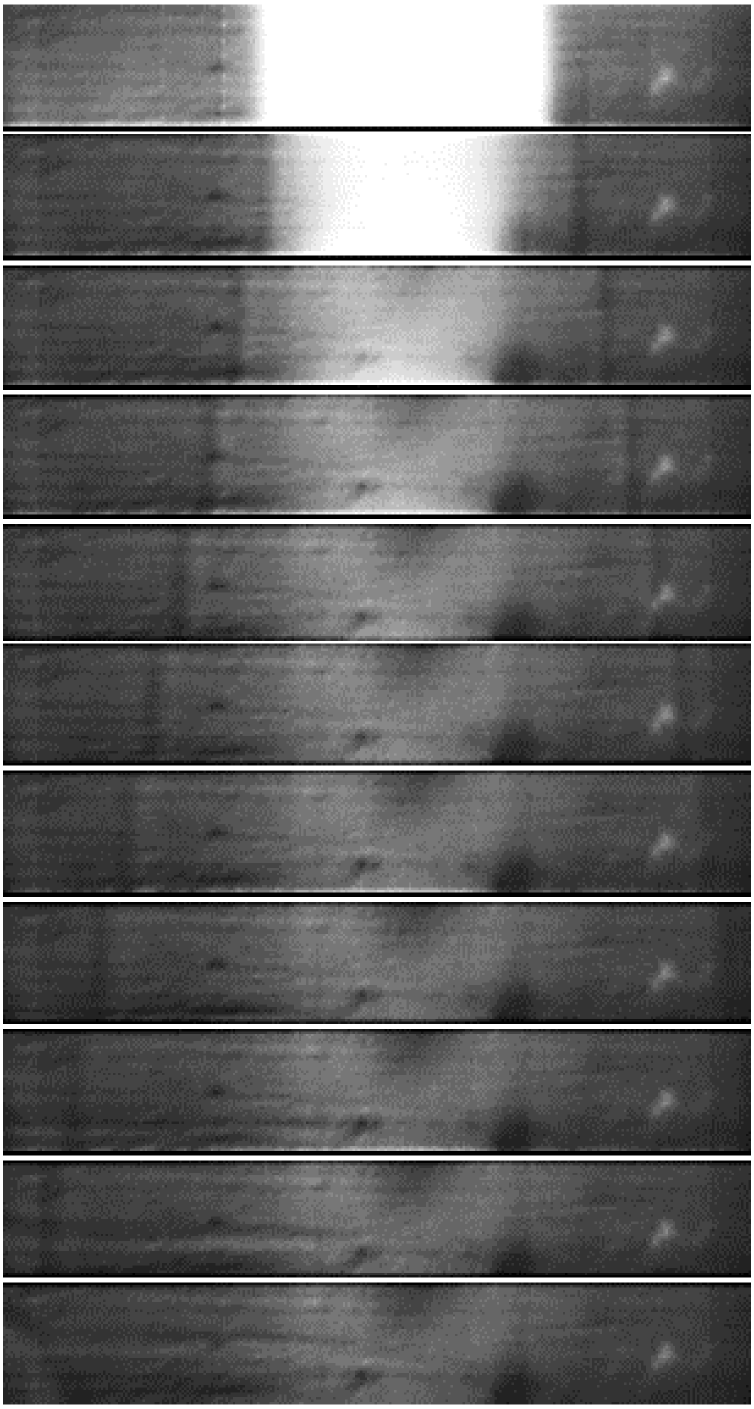


Fig. 5. Sequence of 11 shadow images of shock configuration from the discharge channel, taken with a frame interval of 1.9 μs at a pressure of 120 Torr.

CFD simulation.

2D CFD simulation was based on the time-dependent Navier-Stokes equations (1). The discharge duration is much shorter than the characteristic time of gas dynamic processes. Therefore, in our calculations, we assumed that the energy was input instantly. This was taken into account by imposing the corresponding initial conditions. The deposited energy was distributed among the cylindrical plasma column – so we assume the flow to be 2D with cylindrical symmetry.

$$\begin{cases} \frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} = -\frac{\rho}{x} u \\ \frac{\partial \rho u}{\partial t} + \frac{\partial (p + \rho u^2)}{\partial x} = -\frac{\rho}{x} u^2 \\ \frac{\partial E}{\partial t} + \frac{\partial u(E + p)}{\partial x} = -\frac{\rho}{x} u(E + p) \end{cases} \tag{1}$$

$$E = \frac{p}{\gamma - 1} + \frac{\rho u^2}{2}$$

Fig.4b presents the comparison of CFD calculation with experimental data at the assumption that 21% of the energy of the volume discharge, stored in the electric capacitor is converted into energy of cylindrical shock waves - in the vertical breakdown channel.

Fig. 6. Glow image of controlled discharge localization in low density area. Flow from right to left.

5 Conclusions

An experimental and CFD study was conducted of the 2D flow with cylindrical shock waves from vertical plasma breakdown column 24 mm long. Images of plasma controlled and non-controlled localization were obtained. Flow evolution up to 5 ms after discharge was studied with high-speed shadowgraphy. Speed and intensity of cylindrical shock waves arising from the energy input shock waves were measured; also instability of hot post-discharge channel was visualized. The model of pulse cylindrical energy deposition was used, based on experimental data. Solving the inverse problem shows that 20-22% of the energy of the volume discharge, stored in the capacitor is converted into energy of cylindrical shock waves.

6 Acknowledgement

This study was supported by the Russian Foundation for Basic Research (project no. 15-08-0777 a).

References

[1] Benard N., Zouzou N., Claverie A., Sotton J., and Moreau E. (2012) Optical visualization and electrical characterization of fast-rising pulsed dielectric barrier discharge for airflow control applications. *J. Appl. Phys*., vol. 111, pp 033303, http://scitation.aip.org/content/aip/journal/jap/111/3/10.1063/1.3682568

[2] Znamenskaya I.A., Koroteev D.A., Lutsky A.E. (2008) Discontinuity breakdown on shock wave interaction with nanosecond discharge. *Physics of Fluids*, vol. 20, pp 056101-1-056101-6, http://scitation.aip.org/content/aip/journal/pof2/20/5/10.1063/1.2908010

[3] Znamenskaya I. A., Latfullin D. F., Lutskiĭ A.E., Mursenkova I.V. (2010) Energy deposition in boundary gas layer during initiation of nanosecond sliding surface discharge. *Technical Physics Letters*, vol. 36, pp 795–797, http://link.springer.com/article/10.1134%2FS1063785010090063

[4] Pai D.Z., Stancu G.D., Lacoste D.A. and Laux C.O. (2009) Nanosecond repetitively pulsed discharges in air at atmospheric pressure – the glow regime. *Plasma Sources Sci. Technol.* vol. 18, 045030 (7pp), http://iopscience.iop.org/0963-0252/18/4/045030