SHADOW AND BACKGROUND ORIENTED SCHLIEREN INVESTIGATION OF SHOCK WAVES IN GAS-DISCHARGE MEDIUM

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ABSTRACT: Non-stationary flow arising in gas discharge chamber after surface discharge and combined volume discharge of nanosecond duration in air was experimentally investigated by means of background oriented schlieren (BOS) and shadow technique. The objective of the investigation was to study shock dynamics and to determine the density fields after discharges in air at pressure 6-13 kPa. Using two visualization methods the velocities of shock waves and density fields of the flows were determined.

1 Introduction

The problem of control of flow using gas discharge plasma is considered to be significant in aerodynamics in recent years [1]. The energy input using gas discharges can affect flow parameters [1, 2]. Researches of the gas-dynamic flow resulting from pulse discharge are necessary for analysis of the high-speed flow control possibility. This paper describes the application of background oriented schlieren (BOS) method and shadow method for visualization of flow after surface discharge of nanosecond duration (plasma sheet) and combined volume discharge in air.

Sliding surface discharge of nanosecond duration (plasma sheet) is a distributed plasma formation in the shape of parallel diffuse and bright channels sliding over a dielectric surface [3, 4]. The discharge develops in thin gas layer on the gas-solid dielectric interface. It produces considerable energy deposition in gas layer.

Pulse volume discharge with pre-ionization by ultra-violet radiation from plasma sheets is the special type of combined discharge [5]. Energy of the electric discharge is converted into gas heating, molecules rotation, vibration, ionization, and electrons excitation. Instant input of energy is followed by complicated gas-dynamic processes. Non-stationary flow arises in gas discharge chamber after discharges.

Background oriented schlieren and shadow method were used in the experiments for flow visualization. Schlieren technique is a method that uses the deflection of light due to the change in density field to visualize the density gradients in gas flow. It is commonly used for qualitative investigations. To employ this technique as a quantitative measurement tool, a special calibration has to be employed. The speckle technique was introduced as a quantitative measurement tool [6]. Background oriented schlieren (BOS) is a popular quantitative measurement method [7, 8]. The BOS technique uses the distortion of a background pattern in order to measure the light deflection caused by density gradients in a flow. Two images can then be compared by cross-correlation algorithms [9]. In this study background oriented schlieren method is utilized to visualize quantitatively the structure and the density field distribution in the discharge chamber after pulse discharges in air. Using the results of two methods for analysis of flow with shock waves improves the data of the gas-dynamic flow description.

2 Experimental Setup and Visualization Technique

2.1 Shock Tube

The experiments were performed at the shock tube mounted with a special discharge chamber described in details in [3-5]. Rectangular cross-section of the discharge chamber was the same as the shock tube one (48×24 cm^2). The system could be filled with a working gas – air to a pressure up to 30 kPa. Two side walls of the discharge chamber are the quartz glasses of 170 mm length for the possibility of optical investigations of the discharge area (see Fig. 1).

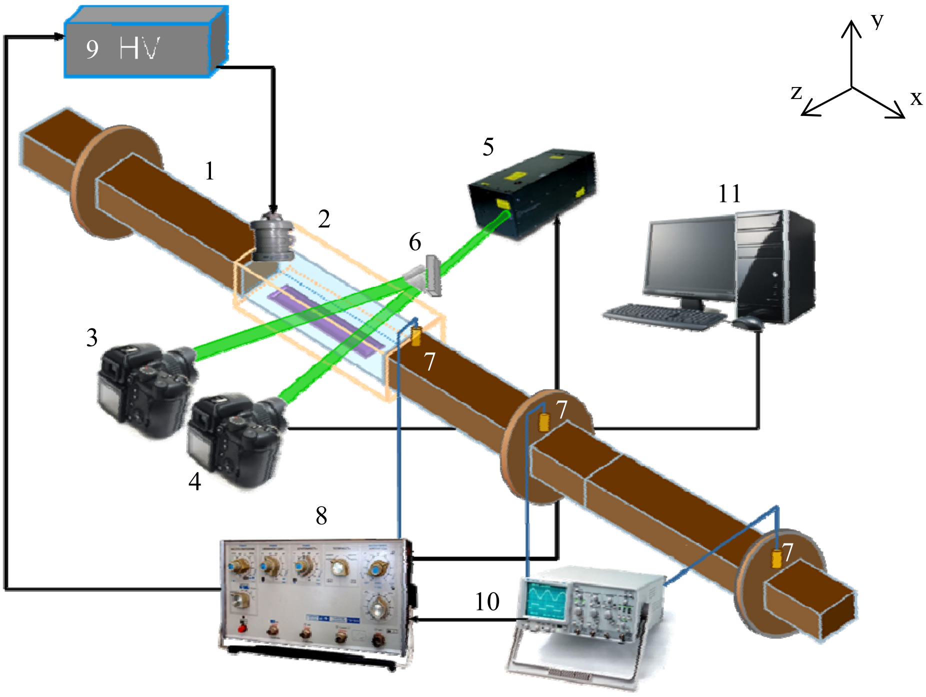

Fig. 1. Experimental Setup: 1 – shock tube, 2 – discharge chamber, 3, 4 – photo camera, 5 – Nd:YAG laser; 6 – optics; 7 – piezoelectric sensors; 8 – delay generator, 9 – spark-gap controller, 10 – oscilloscope, 11 – image PC

2.2 Nanosecond Volume Discharge and Sliding Surface Discharge

Pulse volume discharge with pre-ionization by ultra-violet radiation from plasma sheets was organized in two stages. At first stage (50-70 ns) the plasma sheets on the upper and lower surfaces of the discharge chamber burn. On the second stage pulse volume discharge was realized (see Fig. 2 a, b). To organize a plasma sheet discharges the special electrode configuration was used with discharge gap dimension of 30×100 mm^2. Distributed sliding surface discharges were initiated on two opposite walls of the discharge chamber at distance of 24 mm from each other (see Fig. 2 b, c). Plasma sheets and volume discharge of length 10 cm were started in discharge chamber at pressure 6-13 kPa (air densities ~0.08-0.17 kg/m^3). The value of pulsed voltage was 25 kV, the current ~1 kA. Duration of discharges was about 200 ns that much less than gas dynamic time in shock tube. Shock waves moved from two plasma sheets towards each other in the discharge chamber (see Fig. 2 d).
Synchronizing signal of delay generator started up the high-voltage pulse applied to the discharge gap. After some programmed time the laser pulse was initiated. The time interval between discharge initiation and laser pulse was determined by light sensitive probe. The evolution time of shock wave after discharge ranged from 5 μs to 40 μs in experiments.

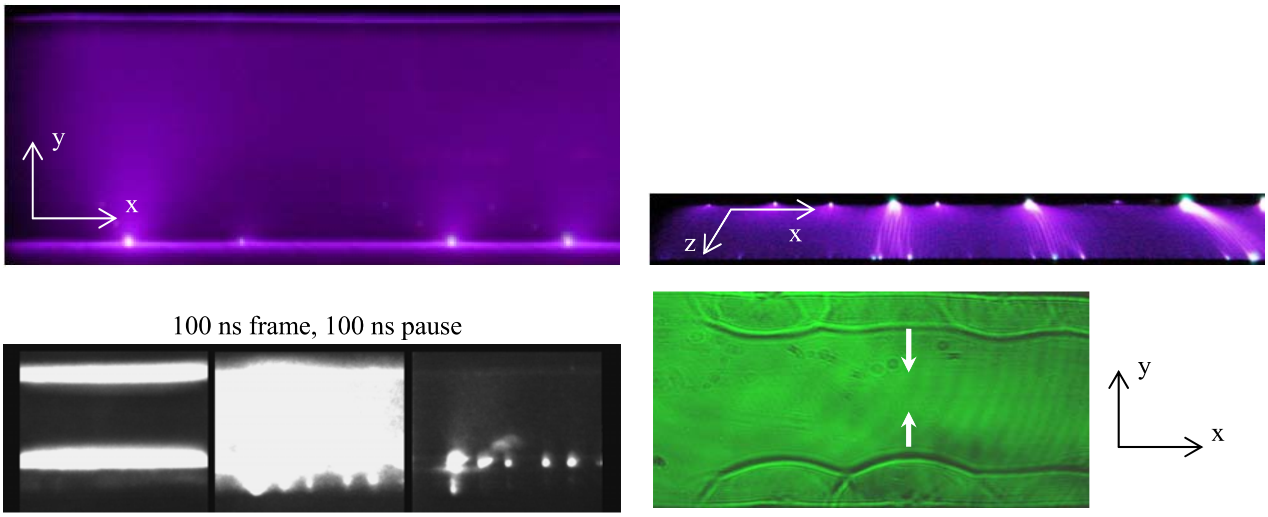

Fig. 2 Images of total glow of volume discharge (a) and time-resolved of volume discharge glow (b) at a pressure of 8 kPa; image of total glow of surface discharge (c) and shadow image of flow field after the surface discharge at a pressure of 13 kPa. (Arrows show the direction of shock waves movement 7.6 μs after discharge.)

2.3 Shadow/BOS System

The flow visualization system includes shadow method and background oriented schlieren. Two methods recorded the flow images at the same moment of time. Focus of BOS camera was set on the background, which consists of a paper with regular distributed dots pattern. Another image was taken by using the shadow method. The angle between the lines of observation of the two methods was about 10 degrees (Fig. 3). The source of light for both methods was pulse Nd:YAG laser (wavelength 532 nm).

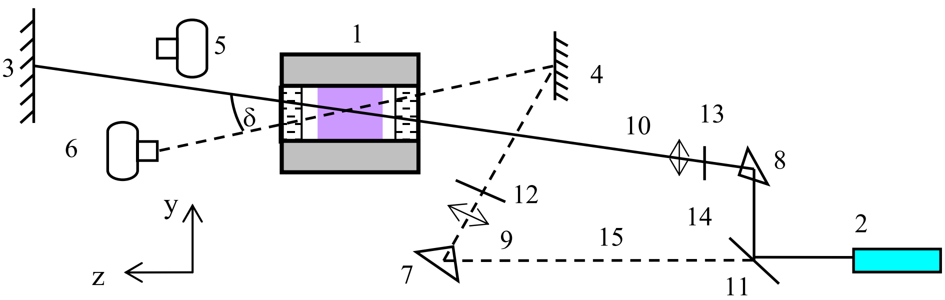

Fig. 3 Optical scheme: 1 – discharge chamber (cross section), 2 – Nd:YAG laser, 3 – schlieren screen, 4 – BOS background, 5, 6 – photo cameras, 7, 8 – rotary prism, 9, 10 – lens, 11 – beam splitter, 12, 13 – filters, 14 – optical path of shadow method (solid line), 15 – optical path of BOS (dotted line).

One BOS image was taken as the reference before the discharge. The other image, containing the flow information, was taken after the discharge with a programmed delay time (1-60 μs). The laser pulse duration was 6 nanoseconds, and it is short enough for the observation of moving shock waves.
The BOS method, introduced by Meier for quantitative visualization of density gradients has wide range of applications because of its simplicity and low equipment requirements. The principle of the technique is the refractive index

variation due to density gradients [7, 9]. The relation between the refractive index and the density is given by the Gladstone-Dale equation for air.

BOS result includes the displacement field in different directions, the displacement vectors and the density field in experiments. The displacement field was determined by direct cross-correlation algorithm with interrogation window size 20×20 pixels. Poisson equation for density was solved numerically [10].

The sensitivity of BOS to large scale flow phenomena (turbulent regions and contact discontinuity) was promising in contrast with shock waves as the width of shock wave was less than 1 pixel in this experiment. Displacement fields with minimum interrogation window size 5×5 pixels are presented in this experiment. After that the shock wave was distinguished as minimum 10 pixels (about 0.4 mm) front. Comparing with the shock wave width of about 10^{-7} m, BOS method is not capable of locating the shock wave front with high accuracy.

3 Results and Discussions

3.1 Shock Waves Evolution in Non-equilibrium Plasma of the Volume Discharge

Shadow images clearly show that a set of semi-cylindrical shock waves is launched near the solid surface after the pulse sliding surface discharge (Fig.2 d). It is a result of quick pressure increase in the energy deposition zone. Dynamics of shock waves fronts was investigated with various delay times after the surface discharge initiation [3]. The average velocity of shock wave front propagation away from discharge area is initially ~800 m/s, and after 10 μs it is about 400 m/s. Later there is a counter interaction of shock waves from two surface discharges from opposite walls. In 40-50 μs after discharge two fronts after counter interaction reach the opposite walls of test section and then reflect.

The results obtained with the shadow and BOS methods are shown in Fig. 4, 5. Density values are normalized to the density of undisturbed gas at the left border of the image. In all the BOS results density in those areas was considered as $\rho=1$ in the legend. 100 units on *x, y* axes correspond to 500 pixels in digital image or 12.24 mm in real size. Size of BOS image was 3120×980 pixels.

BOS method shows shock wave fronts positions similar to shadow method. It yields reasonable density field in the area of shock waves propagation. Homogeneous density in undisturbed region, density rise at the front and density decrease in the center of a semi-cylindrical shock wave are obvious. At the moment of time 5.5 μs, theoretical value of density jump is ~1.4 (obtained from Rankine-Hugoniot relation). The value of density jump at the front according to BOS measurements is lower. This can be associated both with inaccuracy of displacement determination and the error in efficient length of the phase object.

Non-stationary flow field after nanosecond-lasting homogeneous volume discharge is tested in shock tube discharge camera. Energy input in gas volume is quite uniform and is much less comparing to the surface discharge. Shock waves from the surface discharges move in relaxing low-temperature plasma of volume discharge in this case.

Fig. 5 shows the shadow image and BOS result at time 25 μs after volume discharge. Semi-cylindrical shock waves are clearly seen similar to Fig. 4. 20-25 μs after discharge there is a counter interaction of shock waves from two surface discharges on opposite walls. After that the shock wave's fronts are hardly seen.

In relaxing plasma of volume discharge the value of density jump at the front according to BOS measurements is less than in the case without volume discharge.

Analysis of the shadow images of flow field for different delay times after discharges allowed calculating the velocities of shock waves. Fig. 6 shows the dependence of the shock wave position on time after pulse volume discharge. Shock waves move at almost constant velocity during 10-25 μs after discharges. The average velocity of quasi-plane shock wave is about 440±50 m/s and is higher for about 10% than in air. It can be explained by thermal acceleration of shock waves in relaxing plasma of volume discharge. It is known that the velocity of shock waves increases in the area of plasma owing to heating of gas and kinetic processes [11]. The shock waves Mach number can not be precisely calculated because of unknown speed of sound in plasma medium.

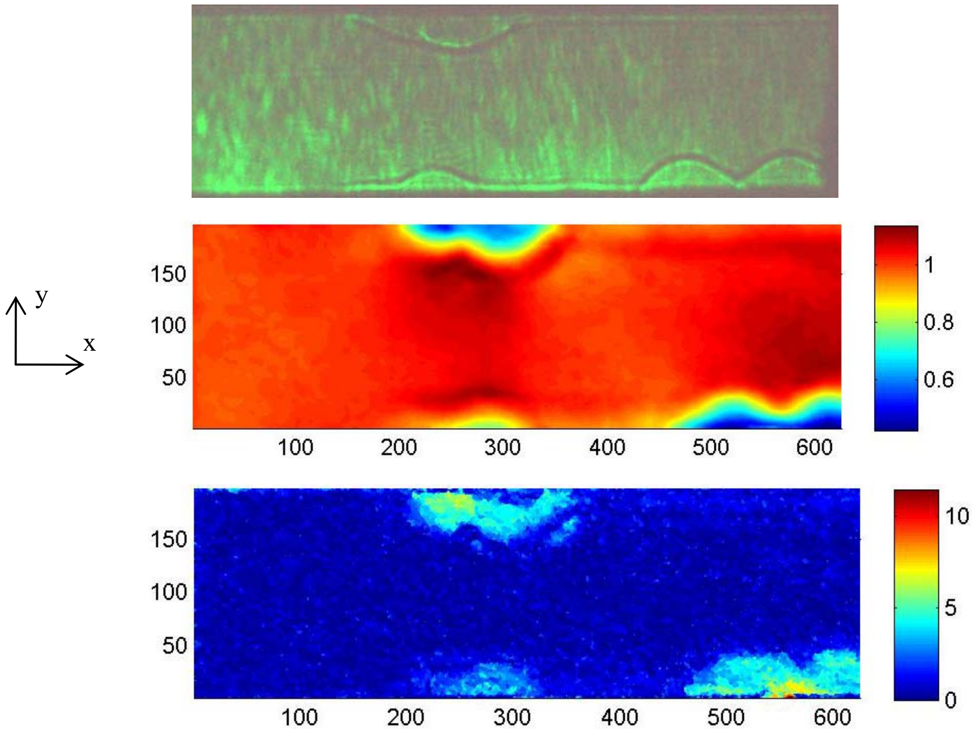

Fig. 4. Images of shock waves 5.5 μs after surface discharges. Shadow image (top), BOS density field (mid) and BOS absolute displacement field (bottom). The initial pressure is 10 kPa.

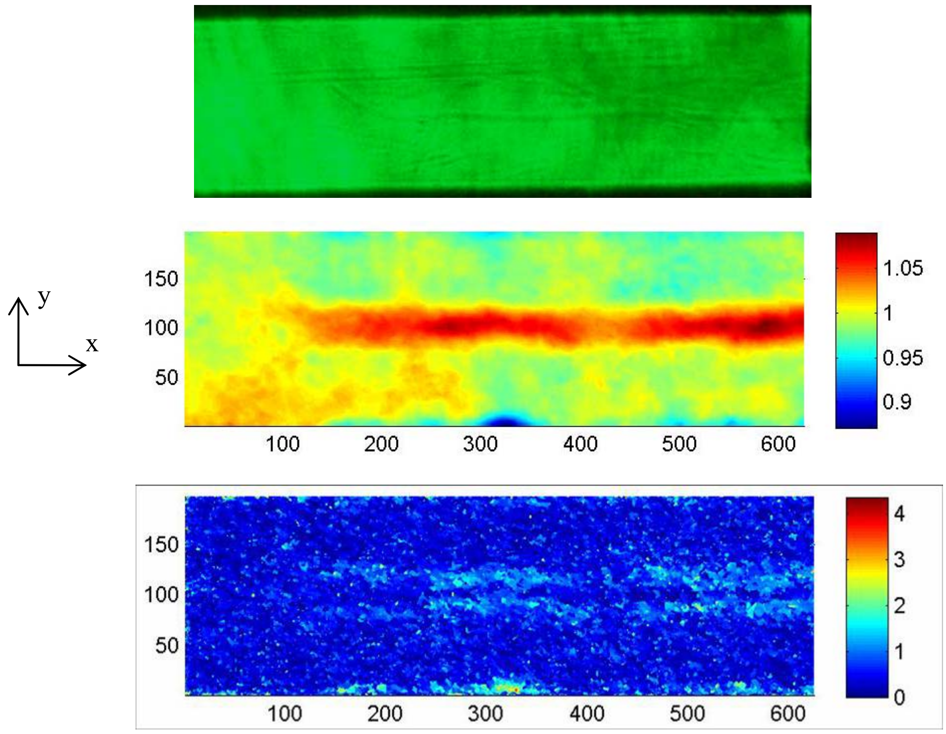

Fig. 5. Images of flow in discharge chamber 25 μs after volume discharge. Shadow image (top), BOS density field (mid) and BOS absolute displacement field (bottom). The initial pressure is 10 kPa.

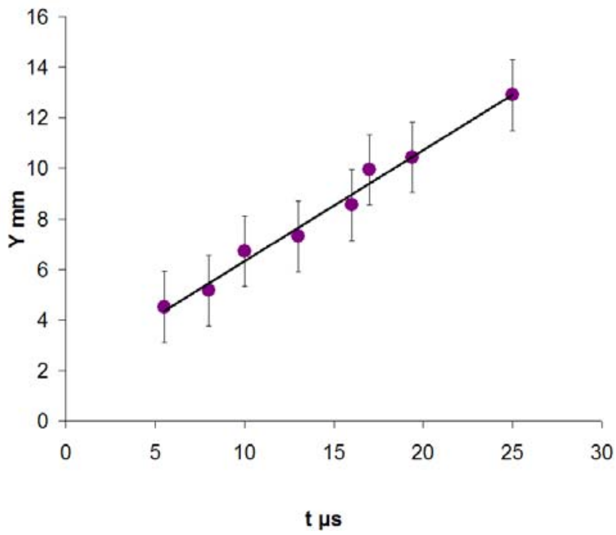

Fig. 6. Average position of quasi-plane shock wave in relaxing plasma of volume discharge at initial pressure of 10 kPa.

3.2 Analysis of Experimental Results

Some difference obviously was in flows after surface discharges and volume discharge. The intensities of shock waves in the flow images after the surface discharge and after the volume discharge are different. After the surface discharge shock wave was always clearly visualized (Fig. 4); after the volume discharge the shock wave is worse distinguishable: 25 µs after volume discharge the front of shock wave is hardly visualized in the shadow image (Fig. 5). Shock waves velocity also is not quite the same. The velocity of shock wave after volume discharge is higher. The reason for these differences is: transversal shock waves from plasma sheets move through the relaxing plasma of volume discharge and the medium temperature in front of shock wave is higher than initial temperature in the test chamber in case of surface discharge. The results obtained by the BOS and schlieren technique indicate that the gas discharge plasma affects the density profile.

The main point of the experiments is the application of two methods for non-stationary flow with shock waves: visualization at the same moments of time. Experiments give a good possibility to compare characteristics and limitations of those two methods. Both are based on phenomena of light refraction in transparent media. In the experiments the flow included high-speed and small-scale objects: shock waves after pulse discharge. The flow is close to 2D. The shadow method shows the position and configuration of the shock fronts with high accuracy. BOS images show the similar configuration but shock front is blurred and the density peak is displaced (it is behind the shadow recorded shock front position). Despite the inexact determination of shock wave position, BOS results show well shock waves in plasma of the volume discharge especially after counter interaction when shock waves almost decay.

It is hard to trace exactly the accurate position of the shock wave front using BOS method, compared to shadow method. So, the dynamics of configurations and velocity of shock waves from plasma sheets were investigated using laser shadow images. The shadow method is more robust with respect to noise, vibrations and modulations of the light source.

The sensitivity of BOS method to small density gradients and the problem of limitation to large density gradients is very important, especially in flow with shock waves. In these experiments the sensitivity to the small density gradient is satisfying; it was correctly reproduced by BOS method. For large density gradients BOS limitation is great. Density jump value on shock front (10^{-7} m width) is up to 2-3. Along with large density gradient, it implies large displacement gradient (i.e. large second spatial derivative of density). In BOS image these large gradients cannot be determined because of limitation of cross-correlation methods based on refractivity.

4 Conclusion

Two methods were used for visualization and analysis of the flow with shock waves after pulse discharges. Application of the shadow and BOS methods for flow visualization at the same moment of time gave complex information about the flow. Flows after surface and combined volume discharges were investigated in the experiments in the discharge test chamber. Shock waves from plasma sheets dynamics and configuration were studied for both cases; also displacement fields and density fields were determined using BOS. The fields of displacement vectors in all directions and density plots were acquired. Quantitative and qualitative results showed the differences between the two flows after these discharges. The use of two methods gave complementary information about the flows.

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