PIV investigation of low-pressure pulse discharge flow

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Abstract The paper presents PIV and shadow visualization of the 3D flow with shock waves, generated by pulse surface discharge. Discharge was initiated inside the low-pressure chamber of the shock tube at pressure of 250-150 torr. High-current, high-voltage (25kV) sliding discharges were initiated on the top and bottom walls of the discharge chamber, forming "plasma sheets" 30x100x0,5mm. The gas flow caused by discharge was studied by PIV and high-speed shadowgraph techniques. With an in-chamber mirror assembly, PIV visualization was carried out from two perpendicular directions, parallel to the symmetry planes of discharge geometry. In case of imaging from transversal direction, laser sheet was aligned along the axis of the discharge channel. Solid particles (TiO_2) were used as tracers, with 532 nm laser as the light source (LaVision PIV device). PIV images analysis showed that shock waves configurations generated by the discharge channels were quite close to cylindrical; though the plasma glow intensity of the discharge channels was not homogeneous – increasing to the end. Thus the electric discharge energy is distributed homogeniously along the sliding surface discharge plasma channels.
Keywords: blast waves, PIV, velocity fields, surface discharge.

1 Introduction

Particle image velocimetry (PIV) has evolved to be the powerful method for flow visualization and has contributed to our understanding of complex flows. A particularly challenging problem is application of PIV to supersonic flows. Quantitative visualization of such objects requires careful consideration of tracer particles, mechanism of flow seeding, and processing of PIV images with regard to highly variable seeding density due to compressibility effects [1,2]. Experiments were performed to obtain instantaneous PIV measurements of the time-evolving flow field behind blast waves produced by exploding bridge wire detonators [3]. It was marked that a significant zone of small-scale turbulence or small-scale instability behind the blast wave, in which the particle images cannot be seen. This limits the PIV measurements to a region behind the shock front ahead of the disturbance.

The paper presents PIV and shadow results of the 3D flow with shock waves, generated by pulse surface discharge. Discharge was initiated inside the low-pressure chamber of the shock tube at pressure of 250-150 Torr. The chamber has rectangular cross-section of 48×24 mm (width×height) with quartz observation windows mounted in side walls. High-current, high-voltage (25kV) sliding discharges were initiated on the top and bottom walls of the discharge chamber, forming "plasma sheets"30x100x0,5mm. A sliding surface discharge is the uniformly distributed plasma formation - system of parallel streamers, sliding on a dielectric surface [4,5]. The development of discharge is rapid, with total time of discharge current not exceeding 300 ns. Integral sliding surface discharge glow image in visible light is on fig.1. As it can be seen, there are some bright channels and areas of diffuse weak homogeneous glow. And the glow sometimes varies along the channels length. The research was aimed at analysis of discharge energy distribution along the channels length – is it homogeneous or bright end means bigger energy release – and thus produces stronger shock waves.

Fig. 1 Surface discharge integral glow

2 Discharge-initiated flow

The gas flow caused by discharge was studied by PIV and high-speed shadowgraph techniques.
A blast wave is a complex-flow structure that propagates as a shock wave as the result of a fast energy release.The formation of shock waves, which can be observed on shadow images right after the plasma sheet initiation [5], is a direct consequence of extremely fast pressure increase in the energy deposition zone due to fast plasma thermalization. High-speed shadow imaging of the growth of large-scale gas-dynamic perturbations from the plasma sheet in quiescent air was conducted. Flow evolution up to 2 ms after discharge was studied.
Blast waves from the channels interact and form a shock configuration moving from surface. At later times (≥50 μs after discharge initiation) thermal plumes emerging from areas of intense channels start propagating, on top and bottom walls they develop likewise. Fig. 2 shows a sequence of shadow images demonstrating the evolution of a zone with higher energy deposition into a large mushroom-shaped vortex near the discharge surface and its growth rate. Mushroom-shaped vortexes growth was caused by forced convection in the flow behind semy-cilindrical shock waves from most intensive channels. Intensive channels integral glow was inhomogeneous along its length.

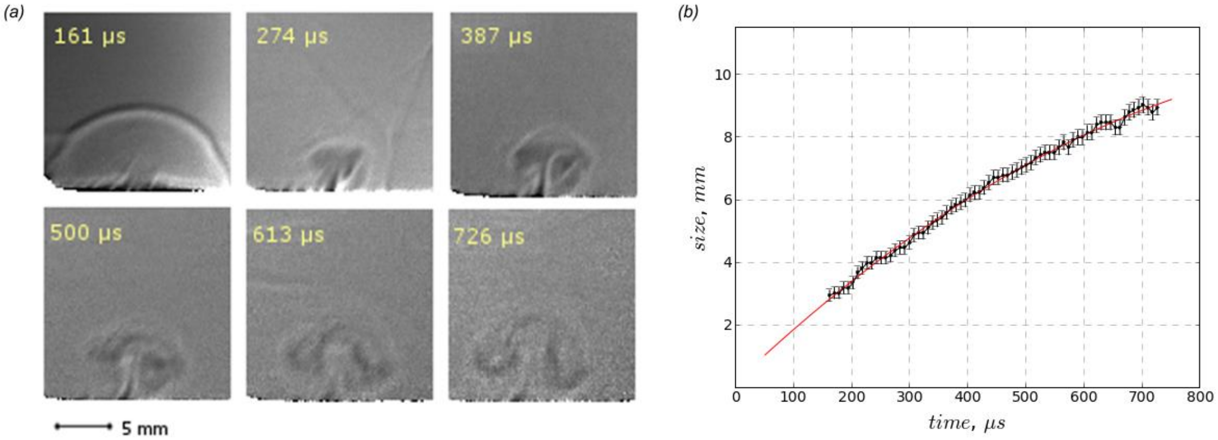


Fig. 2 Shadow images of late post-discharge flow at bright channels.

3 Experimental arrangement

The problem of seeding of the test area inside the tube channel had to be solved specifically for one-run experiments at low pressure. Solid particles (TiO_2) were used as tracers, with 532 nm laser as the light source. Procedure of pre-run seeding was developed. According to it, excessive amount of tracer particles was injected in the camera and distributed using low speed air flow. Then seeded air in tube channel was pumped down to operational pressure. Precise timing was required to eliminate movement and sedimentation of tracer particles up to the moment of the discharge initiation. Flow velocity behind the blast (shock) wave was measured. Evolution of flow velocity behind the shock front was studied for time moments up to 50 μs after the discharge.

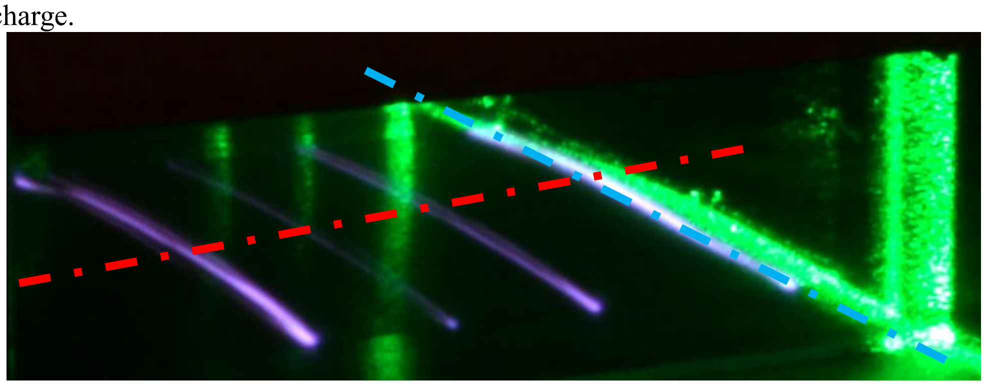


Fig. 3 Laser sheet positions across the discharge channels (red) and along the channel (blue).

With an in-chamber mirror assembly, PIV visualization was carried out from two perpendicular directions, parallel to the symmetry planes of discharge geometry. In case of imaging from transversal direction, laser sheet was aligned along the axis of the discharge channel.

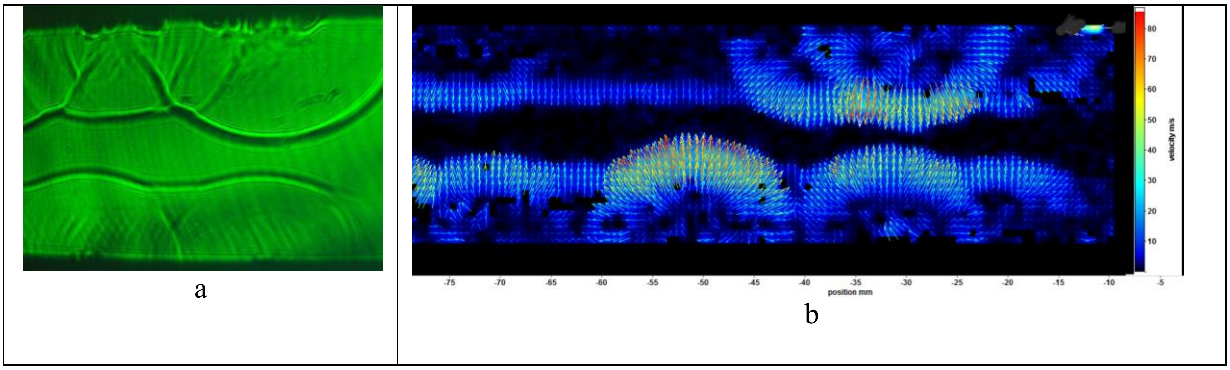


Fig. 4 Shadow and PIV images of shock configuration across the discharge channels.

4 Results and discussion.

Fig. 4a shows the laser shadow image of shock waves spreading from the surface at 175 Torr, 18 µs after the discharge. PIV velocity field for the case of laser sheet direction perpendicular to the channels direction is on Fig 4b. PIV velocity field for the case of laser sheet parallel to the sliding channels direction is on Fig 5.
PIV images analysis show that shock wave configurations generated by the discharge channels were quite close to cylindrical; in spite of the fact that the plasma glow intensity of the discharge channels was not homogeneous on integral glow images – increasing to the end. This inhomogeneity appears to be due to discharge afterglow – streak camera recorded visible light up to 2 µs.
Average flow velocity behind the blast waves decreases from 60-80 m/s to 10-20 m/s. Experimental data analysis have shown the anticipated blurring of the velocity gradient on the front of a blast wave. Width of the velocity step captured by PIV appeared to be in order of 2-4 mm.
Two-dimensional SFD simulations for a compressible gas were conducted based on the time-dependent Navier-Stokes equations. 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 equidistantly spaced channels of diameter d=0.1 mm. Previous investigations have shown that the amount of thermal energy instantaneously releases in the thin gas layer and leads to the formation of shock waves, increases with the density of air including airflow behind the plane shock wave

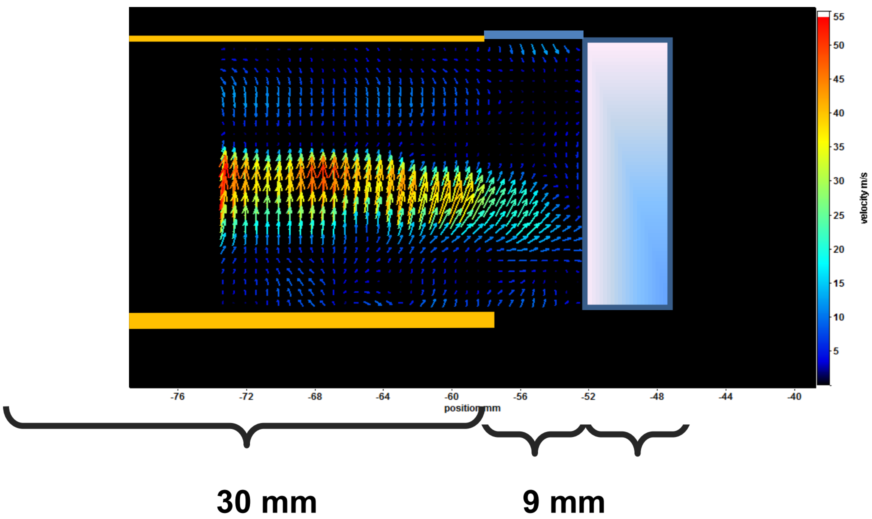
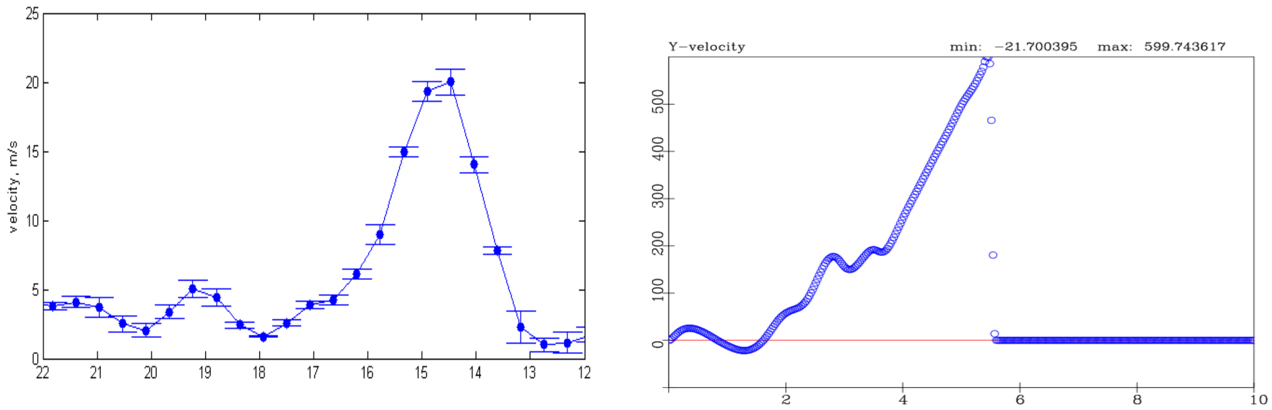


Fig. 5. PIV image of shock configuration along the discharge plasma channel.

Figure 6a shows the spatial profiles of measured velocity behind a discharge blast wave (moving from left to right). Measured PIV data is compared with CFD simulation of velocity on propagating blast wave in the similar moment of time (Fig. 6b). General agreement of the measured data with the assumed profiles is observed. In both cases, we see a sharp increase in the wave velocity after which the velocity decreases and attains an almost zero value. The experimental velocity peak on the front of shock wave is blurred on some extend. The results clearly demonstrate the presence of an appreciable particle lag that exists for nominally 1.5-2.5 mm depending on shock wave speed.



a b

Fig. 6. PIV velocity profile and CFD simulated profile.

5 Conclusions.

The problem solved by particle image velocimetry visualization method was to analyze pulse energy distribution along the sliding discharge plasma channels through matching shock waves configuration and flow velocity field behind them. PIV velocity fields behind blast wave were measured along 2 perpendicular directions. PIV visualization and analysis showed that 3D shapes of shock waves produced by sliding discharge channels were semi - cylindrical; and the velocity flow fields behind them were homogeneous along the plasma channels directions. It means that the electric discharge energy was distributed homogeneously along the sliding surface discharge channels; gas dynamic flow with shock waves produced by nanosecond-lasting plasma sheet discharge is close to two-dimensional.

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