Nanosecond volume discharge in the flow with diffracting shock wave in the rectangular channel

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Abstract. New effects of plasma redistribution shock wave ($M = 2.8–3.4$) diffraction on an obstacle at flow ionization with pulse volume discharge are presented. The obstacle has size $48.0 \times 6.2 \times 1.9$ mm³ and consist of forward facing and backward facing steps on the wall. Localization of the nanosecond combined discharge plasma (with pre-ionization in the volume) in non-stationary gas flow was visualized with plasma glow imaging. It is shown that the discharge images visualize flow evolution structure, mainly - zones of reduced density. Image are compared with 2D CFD simulation.

1. Introduction
Nanosecond discharges proved to be rather effective for active gas flow control [1-4] Pulse discharge is accompanied by a rapid temperature increase, which is caused by the high energy deposition in local area. The gas may be heated in time interval less than 1 μs, plasma zone generates a shock (blast) waves. Their configuration and intensity depends on discharge localization, gas flow structure and density distribution. Surface discharges may be used to control boundary layer [3–7]. Pulse volume discharge with pre-ionization changes dramatically the flow in the supersonic channel [8–10].

The objective of the work is: to analyze the instant redistribution of the pulsed volume discharge plasma at shock wave moving in the channel including in a density field being well-studied on shock diffraction on step, and its further movement in the channel. This redistribution (energy localization) may change the post-discharge flow due to local energy input (see for example [9]).

Shock diffraction on obstacle is one of the most basic phenomena in high speed gas flow dynamics. It has been often adopted as a numerical test for the simulation of unsteady compressible flows [11]. Experimental results were obtained for shock wave diffraction on upward facing and backward facing steps in shock tubes [12–14]. Most of them were obtained using shadow methods and interferometry [11, 12]. Here we recorded the glow of unsteady flow fields at pulsed volume ionization by the discharge initiated at various stages of the gasdynamic process of shock diffraction. Flow in rectangular channel 24x48 mm is close to two-dimensional. Localizing the energy input into specified flow segments and control of the discharge and flow structure are of current interest. We compare the gasdynamic fields experimentally visualized by plasma glow with the numerically simulated density fields of the corresponding complex unsteady flows (with obstacles in the flow). We recorded images of the volume discharge glow distribution in a known field of parameters. Thus the gasdynamic flows can be adjusted via the influence of the localized energy contribution on flow elements.
2. Experimental Setup

Experiments were conducted using a diaphragm shock tube with a special discharge chamber [8]. The energy redistribution of a pulsed volume discharge with preionization from two plasma sheets (electrodes) during its initiation in a rectangular shock tube channel with an oblique shock wave is investigated. The sidewalls of the chamber were transparent windows through which registration was possible. The bottom and top walls were flat plasma electrodes (fig. 1). The initial plane shock wave with homogeneous flow behind it passed over the obstacle in the form of a parallelepiped placed on the lower wall of the shock tube chamber (Fig.1). The instant plasma glow configuration occurring at the initiation of volume discharge was studied. The objective was: to investigate the patterns of nanosecond volume discharge energy redistribution when it is initiated in a non-stationary gas dynamic flow close to 2D in the channel. The discharge was initiated at various stages of the plane shock wave passage through the channel with an obstacle on the wall and after the formation of a stationary flow. By means of a low-inductance shunt we measured the discharge current. The pulsed volume ionization of the gas-dynamic channel section with a length of 10 cm was investigated. Rectangular parallelepiped with dimensions of 48 mm x 6.2 mm x 1.9 mm was fixed at a distance of 1.5 cm from the leading edge of the plasma electrode (downstream). The duration of the discharge current was 150-300 ns, and the duration of the glow was up to 1 μs [8]. The discharge was initiated by 25 kV voltage pulses. The interaction of a plane shock wave with Mach number \( M = 2.8 \)–3.4 and the flow behind it with Mach number 1.2 – 1.4 with this obstacle is considered. Flow visualization is available through the side walls which are quarts glasses. Integrated images of the discharge glow in the flow field were recorded from two sides of the test (discharge) chamber. Oscilloscope curves were measured of combined discharge electric current in flow with moving shock.

![Figure 1. Scheme of discharge chamber channel with a shock wave.](image)

Objects of particular interest are 1) the region of unsteady interaction of the flow with an obstacle on the lower wall (on shock-wave moving past a upward-facing step and backward-facing step; 2) the configuration of oblique shock wave and the flow after initial shock wave had left the discharge area; 3) the interaction of the oblique shock wave with the upper wall and the boundary layer after initial shock wave had left the discharge area.

3. Results and discussion.

In this paper we investigate the first problem - the redistribution of the discharge energy in the flow when moving shock wave is inside the discharge gap. Every glow image is instant visualization of flow structure as far as its exposition is less than 1 μs (gas charge glow time). It is correlated with the distribution of the density in flow due to the effect that it depends on value of an ionization coefficient. Local ionization coefficient is a non-linear function of \( E/N \), (here \( E \) is instant electric field, \( N \) is the concentration of gas molecules).

Four images of flow at different stages of shock wave propagation are on Fig. 2. Grey rectangular is obstacle position. On the first one can see shock wave (movement direction marked with arrow) which
has passed by the downward facing step. Combined discharge glow is separated by shock front – it is instantly localized in low density area [9], the same is on fig. 2b, c. Time $Td$ is 28 and 47 $\mu$s – it is time from front edge of the obstacle to moment of discharge initiation. Behind the diffracted shock the vortex area [11,12] is visualized with intense glow. On fig. 2b ($Td = 28 \mu$s) shock front bottom part is curved after the diffraction; all the flow is in front of it. On fig. 2c ($Td = 47 \mu$s) shock front is already quite straight. On Fig. 2c we can see the flow configuration after initial shock wave had left the discharge area ($Td=173 \mu$s): the oblique shock wave; its interaction with boundary layer at the upper wall, separation zone at the backward facing step. This is stationary flow slightly changing in time.

It is important to mark that the gas flow almost does not change in image exposition time and it changes dramatically after the discharge, supplying locally electric current energy in structural flow [9].

![Image](image1.png)

Figure 2. Photo images of discharge glow at different stages of gas dynamic process.

Numerical simulation of the flow was made based on two-dimensional unsteady Navier-Stocks equations in order to understand the detailed flow structure evolution for experimental parameters. Two-dimensional computer simulations of density fields were compared to discharge glow distributions [10,15]. The non-slip boundary conditions were used for solid wall boundaries and “non-reflecting” ones were used on open boundaries. Instant discharge images being obtained were compared to CFD calculations of 2D non-stable flow, visualized in gray scale. Image of discharge glow at shock diffraction and CFD simulation of the same stage at $Td$ 17 $\mu$s are on fig.3. Vortex behind the step (lowest density area) is the brightest zone, the darkest is area behind bow shock formed in supersonic flow in front of upward facing step.
Figure 3. Instant photo image of discharge glow at shock diffraction (left) and CFD simulation of the same stage (right).

The analysis of oscilloscope curves of discharge current in flow with moving shock allowed us to investigate the dependence of the time and amplitude characteristics of the discharge current on the instantaneous structure of the gas-dynamic flow. On Fig. 4: Mach number $M = 3.23 \pm 0.05$, SW position was: $x = -1$ mm; 9 mm; 14 mm; $x = 26$ mm in 1-4 subsequently. It was shown that they do not differ greatly while shock wave is inside gap. When part of energy is directed into vortex low density channel we have a small changing on the curve (3 on Fig.4).

Figure 4. Oscilloscope measured combined discharge current curves in flow with moving shock.

When the shock wave passes between the plasma electrodes (on the upper and lower walls of the channel), the initiation of the discharge leads to the localization of almost the entire discharge current in channel area separated by the shock front [1]. At the same time, the front curved when the shock passed over the obstacle and part of the energy was localized to the vortex area behind the obstacle.
4. Conclusions
This work is focused on details of shock wave interaction at pulse discharge initiation in channel with step, which was not previously explored in available publications. We investigated the patterns of nanosecond volume discharge energy redistribution when it was initiated in a non-stationary gas dynamic flow (close to 2D in the rectangular channel).

We recorded the instant glow images of unsteady flow fields at nanosecond combined discharge ionization being initiated at various stages of the gasdynamic process. Shock wave \((M = 2.8 – 3.4)\) diffraction on rectangular parallelepiped on the wall and transition to stationary flow \((M_f = 1.2-1.5)\) with oblique shock wave was visualized with volume discharge at submicrosecond exposition (discharge glow time). Volume discharge energy is instantly redistributed in non-homogeneous density field.

When shock is moving inside gap (10cm long) at pulse discharge initiation moment \(T_{dis}\), discharge glow is localized in low density zones: in front of shock and in vortex at downward step wall.

When initial shock wave had left the discharge area, oblique shock wave, formed downstream the obstacle, separation zone at the backward facing step and the shock-boundary layer interaction on the opposite was are visualized in channel flow. Upward facing step has a dark zone in front of it - due to bow shock formed in supersonic flow (with high density area behind it). The calculated flow density distribution patterns at different time moments had been obtained by solving the Navier-Stokes equations [10]. We compared the gasdynamic fields experimentally visualized by plasma glow with the numerically simulated corresponding grey scale density fields of the 2D flow. Oscilloscope measured current curves in flow with moving shock were analyzed. Thus we can predict the plasma energy pulse localization in non-stationary flow. Sharp density gradients attract energy fluxes and this is followed by flow alternation. A predictable volume-discharge current redistribution seems to be promising in flow control in channel flows.

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