Localization of a combined pulse discharge within a gas with a rectangular obstacle on the channel wall

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Abstract. Analysis of plasma energy redistribution was conducted on the basis of experimental study of combined volume discharge of submicrosecond duration at its initiation in a gas-dynamic flow in rectangular channel with an obstacle. Shock wave diffraction on the obstacle (parallelepiped) on the channel wall was visualized. Effects of plasma localization at upward facing step and backward facing step were experimentally discovered and studied. CFD simulation patterns of the gas dynamic non stationary flow were compared to instant flow glow images.

1. Introduction
A large number of researches are devoted nowadays to the interaction of gas discharge plasma with the gas dynamic flows parameters and structures. Of particular interest are the studies of the impact on the separation zones in high-speed flows with shock waves, both in the external flows and in the channels. Due to separation formation in flow near the step, the distribution of pressure, density, temperature changes in the separation area [1-4]. At supersonic speeds shock waves are formed; pressure changings are much stronger both at downwind and upwind side than those in subsonic flows. Plasma control of separation zones was shown to be rather effective, especially at using of pulse discharges [5-10]. Here we present the phenomena of pulse discharge energy redistribution in high speed flow over the step evolution which may be used for local flow control.

2. Experimental setup
The setup was a diaphragm shock tube with a rectangular channel cross-section of the internal size 24x48 mm² (figure 1). In the low pressure section a discharge chamber of the same cross section is fixed. The initial air pressure of 20 to 50 Torr. In the discharge chamber at time moments, synchronized with the position of the shock wave front, a pulsed volume discharge was initiated. Combined discharge - a pulsed volume discharge with pre-ionization by ultraviolet radiation from plasma sheets located on the upper and lower walls of the test (discharge) chamber of the shock tube [11,12]. A voltage pulse with an amplitude of 25 kV initiated the development of nanosecond discharges sliding along the surface of the dielectric, forming plasma sheets that emit in the ultraviolet range and provide pre-ionization of the gas volume. Through the side walls of the chamber (quartz glass) a panoramic instant images of the plasma glow process is recorded [11] (2-angle discharge glow in the non-stationary flow) and shadow high-speed visualization of the gas-dynamic flow with discontinuities.
Various regimes of airflow past an obstacle behind shock waves with Mach numbers from 2.1 to 4.3 after its passage (diffraction) through an obstacle are investigated. The experimentally measured rate of the flow behind the shock wave decreased from 700 - 800 m/s to 300 - 200 m/s to 6 - 7 milliseconds.

The change in the glow field (localization of the discharge near the step) is shown when it is initiated sequentially in a supersonic, transonic, subsonic flow in both laminar and turbulent flow. Plasma radiation is determined by the local value of the reduced electric field $E/N$ ($E$ is the electric field strength, $N$ is the concentration of molecules) [11-13]. The discharge in the flow is localized in the form of a straight short-lived plasma formation with a length of 30 mm and a diameter of 1-2 mm along the upward and (or) downward side of the parallelepiped step at a different distance from the lower wall and from the step (see figure 2). The plasma glow (figure 3 a,b) time is 200–1000 ns with a discharge current duration of 200–300 ns.

**Figure 1.** Scheme of shock tube with test (discharge) chamber.

**Figure 2.** 1 – Downwind localization; 2 – Transition from downwind localization to upwind localization; 3 – Upwind localization (after 1200 mcs).
Figure 3. Images of combined nanosecond discharge glow near the step from opposite windows (a,b) and scheme of the flow (c).

3. CFD simulation
A numerical two dimensional simulation of the investigated non-stationary gas flow was conducted. Quasi-two-dimensional process of plane shock wave diffraction on a rectangular obstacle and the formation of a flow in a rectangular channel were simulated basing of the Navier-Stokes equations. The non-slip boundary conditions were used for two wall boundaries and "non-reflecting" condition were used on two open boundaries. The results of the numerical visualization of the density, pressure, Mach number and velocity fields (figure 4) were compared to the experimental patterns of discharge glow in the flow fields. Especially the dynamics of density fields in the zone around the obstacle was analyzed: CFD images of density fields were compared to instant discharge glow patterns.

4. Discussion
It is shown that an evolution of the energy fluxes position of the discharge plasma is connected in a complex way with a change in the local flow structure of separation zones during a flow development around the forward-facing step and backward-facing step. A series of compression waves were formed...
upstream of the obstacle and they combine to form the oblique shock wave at distance about 1-1.5 cm in front of it. Its intersection with upper wall (plasma sheet) is also visualized with weak glow.

![Velocity vectors](image1.png) ![Velocity vectors](image2.png)
![Density](image3.png) ![Density](image4.png)
![Pressure](image5.png) ![Pressure](image6.png)
![Mach number](image7.png) ![Mach number](image8.png)

**Figure 4.** CFD simulation of the channel flow after shock diffraction on the step.

Vortex behind the step (the low density area) is the zone of intense glow - it is visualized just after shock diffraction (figure 3). Vortex in separation area in front of the step is formed later as soon as the flow velocity reduces in the shock tube flow and the boundary layer increases. When the density gradient at the upwind facing side becomes grater the bright line moves to it from backward facing side (scheme on figure 2). The dark area is behind bow shock formed in supersonic flow in front of upward-facing step. So the discharge glow visualizes the redistribution of pulse volume discharge energy in cylindrical vortexes of plasma transversal to main flow direction – plasma formations with submicrosecond lifetime. After discharge initiation quasy-cylindrical blast waves should develop and change the flow around the step.

**Conclusions**

The experimental data and numerical simulation on separation zones in the upward-facing or/and downward-facing step zones are shown to be areas of discharge energy localization at different flow parameters. The possibilities of the high speed flow control around a step on the basis of studied phenomenon of discharge self-localization are motivating for further researches.

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References

[1] Chang P K 1970 Separation of flow (Pergamon Press, Oxford)
[2] Cheeda V K, Kumar A and Ramamurthi K 2014 Shock Waves 24 157
[3] Pankaj M Nadge and Govardhan R N 2014 Experiments in Fluids 55 1657
[4] Takayama K and Inoue O 1991 Shock Waves (Springer) 1 301
[5] Ruisi R, Zare-Behtash H, Kontis K and Erfani R 2016 Acta Astronautica 126 354
[6] Ukai T, Russell A, Zare-Behtash H and Kontis K 2018 Physics of Fluids 30 116106
[7] Bayoda K D, Benard N and Moreau E 2015 J. Appl. Phys. 118 063301
[8] Kinefuchi K, Starikovskiy A Y and Miles R B 2018 Phys. Fluids 30 106105
[9] Leonov S B, Firsova A and Houpt A W 2018 Conference Series. IOP Publishing 1112 012005
[10] Arkhipov N O, Znamenskaya I A, Mursenkova I V, Ostapenko I Yu and Sysoev N N 2014 Moscow University Physics Bulletin 69 96
[11] Znamenskaya I A, Ivanov I É, Kryukov I A and Kuli-Zade T A 2002 Journal of Experimental and Theoretical Physics 95 1033
[12] Chen X, Sha X G, Wen S, Lu H B and Ji F 2018 Visualization of three dimension shock wave in hypersonic gun tunnel using electric discharge: 18th International Symposium on Flow Visualization (Zurich, Switzerland)