Visualization of the shock wave diffraction on the wedge in a rectangular channel

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Abstract. The evolution of a shock wave interaction with a boundary layer on the surface of a shock tube channel after its reflection from a thin wedge is investigated. Visualization of the incident plane shock wave, the bow detached shock wave and flow behind the wedge in 48x24 mm channel was performed using the shadow method based on high-speed recording. The zone of boundary layer separation that occurs when the plane attached bow shock intersects with the channel wall is visualized on the basis of the pulse discharge glow recording. The flow evolution at incident shock wave Mach number of 2.3÷3.8 for the time interval up to 5 ms after the diffraction is investigated. The obtained data is compared with the corresponding CFD results: a numerical simulation based on the Euler equations of a nonstationary two-dimensional flow was performed under experimental conditions.

1. Introduction
Effect of the discharge glow intensity redistribution in a gas flow with density inhomogeneity is well known. It can be used for flow visualization and sometimes for flow control. Stationary supersonic flows in wind tunnels at low pressure were visualized by Alfyorov [1]. An oblique shock diffraction on a 35° wedge was visualized by the nonequilibrium nitrogen plasma [2]. Discharge illumination technique was used to visualize density field of a supersonic air flow around the cylinder [3] in wind tunnel; good correlation between numerical simulations and experimental results was shown despite the presence of the discharge plasma. The pulse volume discharge with pre-ionization by plasma electrodes was used in the experiments for 3D visualization of the flow around a combined conic-cylinder model [4] and cone [5].

The discharge visualization method is invasive: discharge initiation in gas flow influences the flow parameters and structure. The main effect is due to the gas heating by the discharge electric current. If the energy input (gas heating) duration is short enough, the influence of the discharge on the flow immediately after the breakdown may be negligible. It works in case of the pulse discharge of submicrosecond electric current time. In time of less than 100 nanoseconds after the discharge initiating shock (blast) waves may be generated on boundary of plasma area. Shock waves change the flow dramatically. This effect may be used for flow control [6–8].

The gas dynamic process in pulse discharge in flow occurs after the discharge glow relaxation, so we can get the instant gas flow image through integral glow recording. The plasma glow visualizes low density areas and density gradients: vortices, shock waves, boundary separation zones instabilities.
2. Experimental setup

In this paper pulse volume discharge with ultraviolet pre-ionization by sliding surface discharges was initiated in different moments of shock wave diffraction on wedge in shock tube channel. Plasma energy redistribution was analyzed and also plasma glow recording was used for flow visualization of non-stationary 3D flow. Shock tube mounted with special electric discharge chamber was used for study of non-stationary interaction of shock wave with wedge in the channel and discharge redistribution at pulse ionization of the non–stationary flow. The setup configuration is shown in figure 1. Shock tube had a channel (low pressure section) with the rectangular profile 24x48 mm. Shock waves with Mach numbers $M = 2.3 \div 4$ were studied. Helium was a driver gas and the air as a driven (tested) gas. The discharge chamber was mounted with the shock tube’s channel and it had quite the same rectangular profile. Top and bottom of the chamber were the plasma electrodes; they also generate the ultraviolet glow for the homogeneous pre-ionization of discharge (and flow) area. Special binary configuration of discharge section allowed obtaining the homogeneity of the main discharge in the flow area 100 mm long [6,7]. Special type of discharge is involved for pulse volume discharge visualizing method: pulse volume discharge with ultraviolet preionization by radiation from the sliding surface discharges. High initial discharge space homogeneity is due to volume ultraviolet preionization by radiation from the sliding surface discharges, which form plasma electrodes. The sidewalls were made of quartz glass to make the discharge glow and gas flow visible by the optical means, and using shadow technique. The length of the discharge gap was 100 mm. Pressure in low pressure and high pressure sections before the diaphragm break was controlled by pressure-gauges. Special synchronization scheme was formed to make the discharge initiation on the different stages of shock wave interacting with the wedge in the discharge chamber. Flow spectrum analysis showed that the luminescence intensity main source is the nitrogen gas second positive band $N^{++}$. The glow intensity decays in motionless gas at $100\div200$ ns depending on the pressure. In structured flow glow area is localized in zones of high $E/N$ ($E$ is electrical field; $N$-particles concentration. The integral nanosecond-lasting discharge glow redistribution was recorded by photo cameras (figure 1).

![FIGURE 1. Experimental setup and integral photo cameras recording.](image)

The wedge of $10^\circ$ angle was mounted in the discharge camera of shock tube (figure 2). When shock wave was interacting with a wedge, passing through the discharge section, discharge was switched on. Plasma glow redistribution in non-stationary inhomogeneous flow was recorded at 3 or 2 angles of view through camera windows.
3. Numerical method
A two-dimensional numerical simulation under experimental conditions was conducted. We use a framework of time-dependent 2D Euler equations model for numerical simulations. A comparison of numerical data and shadow images of a 2D flow after shock wave interaction with the wedge area and channel walls was conducted. Adequacy of the used model is supported by experimental shadow images of the flow area.

The computational domain has taken assuming the symmetry plane of the flow existence. The mathematical model of the Euler equations for two-dimensional unsteady flows in Cartesian coordinates was used. The initial parameters correspond to the undisturbed flow at a fixed gas pressure of 10⁻⁸⁻⁰ Torr. The system of Euler equations was solved using finite volume MUSCL type scheme with spatial reconstruction of the fifth order and the third-order Runge-Kutta approximation on time. The flows through the cell faces were calculated using the approximate AUSM method for the Riemann problem. CFD computations were performed at various grid point numbers. Accuracy of numerical scheme up to fifth order has been demonstrated. In comparing CFD and glow and shadow images, the plasma localization and gas dynamic configurations of the shock wave – pulse discharge interactions were understood.

4. Flow analysis
Figure 3 presents shadow images of flow in front of wedge after shock wave diffraction recorded with high speed digital camera Photron Fastcam SA5. Distance between the shock wave and the nose of the wedge was measured and its evolution in time is analyzed. After reflecting from wedge front the bow detached shock is stable for some time (figure 3a); the distance d is about 1 mm. CFD simulation shows that flow along the wedge is quickly changing and compression waves begin to influence the nose shock, it moves away from the wedge (figure 3 b) in some moment of time 400mcs < t_cr < 600mcs depending on Mach number (figure 4).
FIGURE 3. Shadow images of the flow at the nose of the wedge.

FIGURE 4. Distance between the shock wave and the nose of the wedge: evolution in time.

CFD density flow field at different moments of time are in figure 5. Time is 50; 100; 300; 500; 700 mcs after the shock interaction with wedge nose.

Pulse discharge was switched through synchronization system in different moments of time \(10 < t < 1000\) mcs and the integral plasma glow images were recorded. Plasma glow redistributed into low density (high E/N) areas. Figure 6a is the pulse volume discharge glow in test camera with a wedge in quiescent air at pressure 50 torr. While the shock wave is passing along the wedge (from
right to left), it is shaded by the wedge and is not seen on the shadow images. The discharge glow concentrates in the low pressure area in front of the shock wave; phenomenon of discharge self-localization in low density area front of shock is recorded in figure 6 b, c. The shock front is visualized on instant glow images. When shock had passed the wedge, in separation zone is formed at the rear side of it. Discharge energy is localized in the vortex separation zone (figure 6d). Discharge energy input is in the small area behind the wedge.

**FIGURE 5.** 2D CFD simulation of shock wave diffraction on the wedge.

Figure 6e presents the image of the of shock-boundary layer intersection at late moment of time in case when wedge rear side is off the discharge gap zone. Discharge glow visualizes the separation line of shock-boundary layer interaction (see also two last CFD images). It is already close to the front edge line of the wedge nose.

Shadow digital high speed video images (figure 7 a,b) showed that discharge energy input in the wedge rear side separation zone produce a blast wave configuration close to wedge surface and its action on wedge and flow is rather appreciable (figure 7b). Energy release in separation zone of shock-wall interaction is shown to be not so appreciable; blast waves from plasma channel spreading along the glass window wall decay on their way to the wedge bow shock figure 7 a. So the intersection line visualization is the main result of the plasma redistribution into the separation zone there.

5. **Conclusion**

The evolution of a high speed gas flow at shock wave diffraction on the wedge in rectangular channel is investigated at pulse volume discharge initiation on different non-stationary process stages. Visualization was performed using the shadow method with high-speed digital video recording and on sub microsecond-lasting discharge plasma glow recording. If the flow area is shaded with wedge, it cannot be recorded by the shadow method; there the discharge visualization works: gas low density areas are visualized. Pulsed volume discharge with preionization by ultraviolet radiation from plasma sheets is switched in channel area 48x24x100mm. A 2D CFD simulation of a nonstationary gas
dynamic flow was performed under experimental conditions. The CFD data was compared with the corresponding experimental data. Discharge glow was concentrated in front of shock wave and in 2 separation zones: 1. at shock-wall boundary layer on the glass wall interaction and 2. at the vortex separation zone at the discharge rear side after shock diffraction. It was shown that those blast waves from plasma channel spreading along the glass wall decay on their way to the wedge and do not influence the bow shock significantly. The blast waves in the rear side separation zone may influence the flow significantly. Both serve to visualize the non stationary flow structure.

FIGURE 6. Images of pulse discharge glow on different stages of shock diffraction on the wedge.
FIGURE 7. Shadow images of flow evolution after pulse discharge: up – wedge nose; down-behind rear wall.

Acknowledgement
This work was supported by Russian Science Foundation Grant (the projects No 18-19-00692).

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