Nanosecond discharges in a non-stationary flow around an obstacle

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Abstract. The purpose of the work is to study the effect of a pulsed surface discharge (plasma sheet) on the transverse flow upon its initiation in an unsteady gas-dynamic flow in a channel with an obstacle on the wall. Also a comparison with the effect of a pulsed volume discharge under similar conditions was studied. The dynamics of the blast waves propagating from the separation zone behind the obstacle after self-localization of the discharge plasma there is investigated.

1. Introduction

Interest in use of gas discharges as plasma actuators is growing due to need for devises for active flow control. Lack of mechanical parts, high response frequency make nanosecond discharges appropriate for both external and internal flows. Although the flow induced by these actuators acquired much attention, the effect that the external flow on the actuator plasma configuration itself must also be considered, especially the influence on unsteady high-speed flows. It should be noted that in recent years special attention has been paid to the separation flow control near the steps [1], dielectric barrier discharge (DBD) plasma actuators are in focus. The primary objective of the presented study is to examine the characteristics of nanosecond discharges when switched to an unsteady flow generated in a shock tube. The flow in the shock tube, which is often used in various shock waves studies, is universal in that it contains a range of flow regimes from sudden changes in pressure and density to relatively uniform regions of high-speed flow. High-speed shadow imaging is used to visualize the flow.

Nanosecond discharges proved to be sufficiently effective for active control of the gas flow [2 - 5]. Surface discharges can be used to control the boundary layer [4, 6, 7]. In particular, DBD-based plasma actuators show their ability to control the boundary layer [8], delaying separation on aerodynamic surfaces and turbine blades [9], and controlling the transition [10] from laminar to turbulent flow. They consist of pairs of electrodes separated by a thin dielectric insulating plate. A high AC voltage is applied, usually in the range of 2–40 kV p – p (peak to peak). A volume discharge abruptly changes the flow in a supersonic channel [11 - 13].

A pulse discharge is accompanied by a rapid increase in temperature, which is due to the high energy release in the local region. The gas can be heated in a time interval of less than 1 μs, the plasma zone generates a shock (blast) wave. Its configuration and intensity depend on the localization of the discharge, the structure of the gas flow, and the density distribution.
A number of works [14, 15] show the effect of a discharge on various types of flow separation. The influence of the external flow on the performance of the plasma actuator should be studied, especially the influence of high-speed flows which are fast becoming a norm in the operating flight envelopes [16].

In this work, among other things, it was shown that the passage of the shock wave front and the high-speed flow behind it also strongly affects the properties of the plasma configuration. Due to the high speed flow, the movement of electrons and ions along the surface of the dielectric is redistributed. This leads to the formation of redistribution of micro-discharge plasmas.

Numerous studies have shown that a pulsed or pulsed-periodic energy source is necessary for effective action on a high-speed gas flow [17, 18]. As this type of source, pulse discharges are best suited: optical discharge, high-current nanosecond discharges. The duration time of gas heating realized by a nanosecond discharge is less than the characteristic times of the gas dynamic flow. During the breakdown, most plasma instabilities do not have time to develop. Thus, pulse discharges are means for rapid and energy-efficient impact on the flow. The effect of the discharge on the flow is mainly determined by the energy amount [19], the configuration of the discharge plasma region, and the parameters of the initial gas flow. A pulsed surface discharge in air generates a shock wave, thereby transmitting the pulse to the surrounding gas. An important task is to determine the proportion of discharge energy spent on the formation of gas-dynamic perturbations, especially shock wave.

In [20], the authors investigated exactly this type of discharge - a pulsed surface discharge at atmospheric pressure. They showed that the energy stored in the capacitor is dissipated in the discharge channel, in the internal resistance circuit (including the spark gap), and in a parallel resistor. For the initial energy E = 2.7 J. usually 80% of the accumulated energy is transferred to the discharge. Most of this energy is dissipated in the discharge during the first current pulse, which lasts about 300 NS.

In this paper we studied the possibility of flow control in the rectangle channel with a parallelepiped obstacle on the wall. First, we studied experimentally and conducted the CFD simulation of the flow on shock wave diffraction on the obstacle and flow behind it. Then we focused on experimental investigation of the pulse volume discharge with pre-ionization from plasma sheets localization in the channel in quiescent air at different pressure values and studied with high speed shadowgraphy the arising flow with shock waves. Instant plasma glow images are compared with consequent CFD patterns.

2. Experimental setup
The experiments were carried out on a shock tube with a special discharge chamber [21]. A discharge of the “plasma sheet” type, as well as a pulsed volume discharge with preionization from the plasma sheets were initiated in the flow at different stages of the plane shock wave passage through the channel with the obstacle. To produce the two plasma sheets (a set of channels sliding over a dielectric surface), we used the electrode configurations on lower and upper walls of the chamber shown in Figure 1. On the upper wall, the electrodes are arranged in the same way as on the lower wall. The electrodes of the sliding discharge were made from 0.1 mm thick cooper foil located on a dielectric surface. The initial plane shock wave with a uniform flow behind it passed through an obstacle in the form of a parallelepiped with dimensions of 48.0 mm × 6.2 mm × 2.0 mm, placed on the lower wall of the discharge chamber (see Figure 1). The flow velocity decreased to transonic values after 600-700 μs. The duration of the discharge electric current was 200–600 ns.
Two types of pulsed discharges were initiated in the flow 1) surface mode 2) volume mode. Discharges sliding along the dielectric surface (plasma sheets/plasma electrodes) were initiated on the lower and upper surfaces of the channel on a 100 mm length distance and 30 mm wide (see Figure 1b). The distributed surface discharge consists of system of parallel discharges developing crosswise the flow [22].

The waveforms of the surface discharge current in the flow is shown in Figure 2.

**Figure 1.** Schema of the setup and the test camera

**Figure 2.** The waveforms of the pulse surface discharge current in the flow behind the shock wave (M = 3.4). The discharge was initiated at various points in time.
When a discharge was initiated in a stationary gas and in a homogeneous laminar flow behind a shock wave, the shock waves propagating from the plasma sheet, the decelerating contact surface, and the rarefaction wave from the plasma surface boundary [23] were initiated. It was shown that in areas where the intensity of the luminescence of the channels was increased, semi-cylindrical shock waves and a convective plume behind it were initiated, which developed within 400-800 μs. In the presence of inhomogeneities (obstacles) in the boundary layer, the discharge is redistributed. In the zone of flow separation behind the wedge, the discharge contracted into a narrow channel [24].

3. Experimental results

3.1. Shock wave diffraction on the obstacle and flow behind it

Using high-speed shadow shooting (150 thousand frames/sec), the gas dynamic flow was visualized: shock wave diffraction (M = 2.8 - 3.4), flow formation (Mf = 1.2 - 1.5) with separation before and after the obstacle. The obstacle is a combination of steps-towards the flow and along the flow – in subsonic and supersonic modes with different parameters of the experiment. Figure 3 shows sequential frames that visualize the flow section with an obstacle (Shock wave Mach number M = 3.35) and the corresponding frame of the modeled diffraction moment.

The discharge glow in the flow with shock wave was recorded from two angles by cameras; integrated images of the instantaneous field of the discharge glow in the flow were obtained in time up to 80 mcs. Plasma glow patterns [see 25] are compared with the corresponding numerical calculation based on the Navier-Stokes equations solution (see Figure 3b). The waveforms of the discharge current at various stages of the unsteady gas-dynamic process were also analyzed.

The energy of a pulsed discharge of submicrosecond duration is instantly redistributed in an inhomogeneous density field. Previously, three main modes of linear localization of a pulsed volume discharge were recorded in the flow area near an obstacle [21, 27].

![Figure 3. Shadow image and numerical simulation of the flow behind the shock wave in the area of the obstacle.](image)

The diffraction process has been well studied in details by shadow methods with high resolution [27]. A large number of experimental results were obtained for the diffraction of a shock wave on forward and backward steps [27, 28]. The visualization of the flows was carried out mainly by shadow, interferometric methods. As a result of the shock wave passing by the obstacle and its taking out, a bow shock wave is generated with a precursor and a vortex (upwind the obstacle), as well as a reflected shock wave with a curvature of the front of the main shock wave (downwind the obstacle). These elements are observed in the experimental images of Figure 3a.
On shadow image and CFD image Figure 3 one can see diffracted shock, upwind and downwind separation zone. In density flowfield blue color indicates minimum density value – and there the discharge energy is localized.

3.2. Pulse discharge in a flow

3.2.1. Integral visualization method
The discharge in both volume mode and surface mode is localized to the separation zone in the form of short-lived high-current plasma channels in three configurations near the steps. In the volume discharge configuration, part of the energy is redistributed to the region of the passing shock wave (visualizing it). The discharge glow duration is 200–600 ns; during this time, the image of the unsteady flow does not have time to change. After shock had left the zone of the discharge gap, plasma is localized to the zone of the oblique jump behind the obstacle, or to the breakdown channel along the glass wall. In the surface discharge mode at the early stages of flow (up to 700 μs), the glow is intensified in the separation zone behind the obstacle. Figure 4 shows the images of a surface discharge taken from two angles at a time of 370 μs after the shock wave front contact with the leading edge of the obstacle. The intensity of the glow increases many times in the downward separation zone behind the step.

![Figure 4. The integral glow of the pulsed surface discharge in the flow.](image)

Thus, the pulsed discharge glow visualization based on the integral registration made it possible to record lower density zones in the flow. The zones of increased glow intensity represent regions of localization of the discharge energy and are sources of disturbances and shock waves that affect the flow after the end of the discharge current. The zones of intense glow are the regions of localization of the discharge energy. The rise time of the discharge current - surface and volume - is small (tens of nanoseconds); the electric current amplitude reaches 1 A. This leads to a quick pressure jump in the self-localization zone and the formation of discontinuous configurations. After less than 1 μs, the localization zones become sources of explosive waves and disturbances (see Figure 4), which affect the flow as a result of a pulsed discharge.

3.2.2. High-speed shadowgraphy results
High-speed shadowgraphy of the gas-dynamic flow initiated during the localization of the discharge showed that a blast (shock) wave propagates from the separation zone behind the obstacle. Figure 5 shows a film frame: as a result of the initiation of a pulsed discharge, a shock wave begins to propagate from the downwind separation zone (vortex). Also, the explosion in downwind area leads to turbulization of the gas downstream. Shock (blast) wave, arising from the localized plasma energy moves upwards and drifts downstream; it is shown that the resulting blast wave speed significantly exceeds the speed of a blast wave from plasma sheet without flow in the channel. The blast wave velocity in the direction perpendicular to the main flow in the channel is evaluated; it appeared to be up to 1200-1300 m / s. The initial flow regime is restored 50-100 μs after the discharge, depending on...
the stage of the flow around the obstacle. Blast wave is seen on shadow images 3-4 frames (20-30 mcs) in every experiment, and then it decays.

Figure 5. Shadow image of a flow after localization of a linear plasma formation behind an obstacle.

Thus, the effect of a pulsed surface discharge (and volume as well [25]) on the transverse flow is due to blast waves arising at its localization in an unsteady gas-dynamic flow with an obstacle on the wall.

In case of the volume discharge (with preionization from plasma sheets) initiating in flow, part of the discharge energy is redistributed to the region of the passing shock wave or oblique shock wave.

4. Conclusion.
We studied experimentally the possibility of flow control near the obstacle in the rectangle channel of the shock tube in short time. First, we studied the gas dynamics process: the shock wave diffraction on obstacle on the channel wall; it has the form of parallelepiped, which can be considered as a combination of downstream and upstream steps. Step-induced flow during 200-300 mcs is visualized with high speed shadowgraphy. Second, we focused on CFD simulation of the flow on shock wave diffraction and flow behind it evolution based on the two-dimensional Navier-Stokes equations. CFD density patterns were matched with flow glow and shadow images.

Then we studied experimentally the pulse surface and volume discharge plasma glow in the channel in flow behind the shock wave at different Mach numbers. High speed shadowgraphy recorded the arising flow including shock (blast) waves which are produced by the discharge energy localization in the backwind separation zone. The explosion behind the obstacle leads to turbulization of the gas downstream. Blast wave moves upwards and drifts downstream; it is shown that the resulting blast wave speed significantly exceeds the speed of a blast wave from plasma sheet without transversal flow in the channel. The blast wave velocity in the direction perpendicular to the main flow in the channel is evaluated; it appeared to be up to 1200-1300 m/s. The initial flow regime is restored 50-100 μs after the discharge, depending on the channel flow parameters. It affects the high speed flow for 20-30 mcs.

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