Discontinuities dynamics after the interaction of a plane shock wave with pulse volume discharge

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Abstract. The dynamics of the nanosecond combined volume discharge radiation in the air flow with the plane shock wave was studied. Shock wave with Mach number 1.9-4.5 was passing through the discharge chamber and coming out of it while the electric pulse was switched on. The radiation spectra and the discharge currents were registered in the air pressure range 10⁻¹⁵⁻⁰ Torr, a pulsed voltage of 25 kV, and an electric current ~1 kA. It is shown that the electric current duration depends on shock wave position relative to the discharge gap and does not exceed 500 ns at various conditions. As a result of discharge energy input, the shock breakdown occurs with the formation of shock waves and contact surfaces. The high-speed shadow imaging was used to study the flow evolution after the discharge pulse. The experimental data on shock waves and contact surfaces positions is compared with numerically calculated positions, making it possible to determine the amount of thermal energy release during the discharge electric current time.

1. Introduction

Low-temperature non-equilibrium plasma of gas discharges is widely used in many technological processes. In plasma aerodynamics, the generation of controlled plasma areas can be used to reduce dynamic and thermal loads on the surface of an aircraft, to correct the flow regime and to ignite the fuel in the engines [1-4]. Pulse discharges are characterized by a change in the state of a gas and fast heating of the gas as a result of pulsed energy input during the short time of the discharge current. In the initiation of pulsed discharges, the gas heating [1, 3] and shock-wave mechanism [4, 5] determine the action on the flow. Shock waves generated as a result of a sharp change in the state of the medium can noticeably affect the gasdynamic flow. The intensity of these shock waves and their dynamics depend on the processes occurring at the stage of the discharge current.

The combined volume discharge with plasma electrodes providing uniform energy input into the gas due to the diffusive form was studied in stationary air and in the gasdynamic flow with a plane shock wave [6]. The presence of shock waves in the discharge volume may change the discharge current regime, the spatial distribution of charged particles, and the radiation structure and duration [6, 7]. When a pulsed discharge is initiated in a channel gas flow with a shock wave, the discontinuity breakdown conditions are created at the shock front [8].

To use the discharge effect on high-speed flows, it is necessary to know the mechanism of interaction of the shock wave with the plasma region. The goals of the work were registration of discharge current and radiation under interaction of discharge with a plane shock wave inside the discharge volume and
outside it and analysis of the flow field after the discharge on the base of high-speed digital shadow imaging.

2. Experimental Setup

The investigations were carried out in discharge test chamber mounted into the gas-dynamic shock tube [4-6]. A pulsed combined volume discharge with preionization by ultraviolet radiation from plasma sheets was initiated in a discharge chamber. Discharges of this type are used in gas-discharge and excimer lasers [9]. The discharge was realized at operating voltage of 25 kV and switched by a controller. The discharge current was ~ 1 kA, duration was ~ 300 ns. The sliding surface discharges with an area of 3×10 cm² were created on the upper and lower walls of the chamber at a distance of 24 mm from each other. The sliding surface discharges provided the preionization and operated as the electrodes of volume discharge. After reaching a sufficient concentration of electrons, a volume discharge was formed. Two opposite walls of the discharge chamber were the quartz glasses within a length of 17 cm without changing the cross section of the channel (figure 1).

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

The high-speed shadow imaging was used to study the flow pattern evolution after the discharge. Shadow images of the gas-dynamic flow field after the discharge were recorded with a high-speed Photron Fastcam camera with a frame rate of up to 500,000 fps and exposure time 1 μs. The laser beam (532 nm) was formed and directed perpendicular to the glasses of the discharge chamber by the optical system of shadow visualization (figure 1). An important advantage of high-speed imaging was the ability to trace the evolution of the shock-wave structure in the case of each particular experiment, since the discharge structure, as a rule, differs in each case of discharge initiation, and accordingly the evolution of the shock wave configuration is different.

Using the signals of piezoelectric pressure sensors in the shock tube channel, the velocity of the shock waves was measured and synchronization of the processes in the experiments was provided. The
radiation of the discharge were recorded by photo cameras. Multi-frame images of the discharge radiation were obtained using ICCD camera BIFO K011 during 20 μs after discharge. The spectra of radiation are recorded by a spectrometer AvaSpec-2048FT (174-1100 nm). The discharge current is measured by means of a calibrated low-inductance shunt.

The combined volume discharge was investigated in quiescent air and in the airflows behind the plane shock wave at different positions of the shock front in the discharge volume. The length of the discharge region along the direction of motion of the shock wave was 10 cm; the end of the electrodes was taken as the zero value of the coordinate x (figure 1). Thus, the position of the shock wave front inside the discharge volume corresponded to -30 mm ≤ x₀ ≤ 0 (first series of experiments), and beyond the discharge volume 0 ≤ x₀ ≤ 20 mm (second series of experiments). Initial pressure was 10-50 Torr, Mach numbers 1.9-4.5. The shock wave front shifted less than 0.5 mm during the discharge current in the shock tube channel. The triangular marker in figure 1 indicates the discharge gap edge. Arrows indicate the direction of propagation of the shock wave (SW) and concurrent flow.

3. Experimental Results

The uniform radiation of two plasma sheets provides spatially uniform flow volume preionization. As a result, the volume discharge in motionless air (figure 2 a) and in homogeneous flow (figure 2 d) is characterized by a high spatial uniformity. In the presence of a shock wave that is in the discharge volume at the moment of a discharge pulse, the plasma glow is localized in front of the shock wave in the area of low pressure [6, 7]. In this part of the volume the value of the reduced electric field E/N and, correspondingly, the electron concentration are greater in the moment of the discharge phase (E is the electric field strength and N is the concentration of molecules). The photo image of the discharge during interaction with the planar shock wave front inside the discharge volume is shown in figure 2 b, and outside it in figure 2 c, figure 3 a.

Figure 2 Photo images of the discharge glow (a-d) and the sequences of shadow images after the discharge (e, f). The optical axis of the photo camera is perpendicular to the quartz glasses.

Depending on the plane shock wave position front relative to the discharge volume, the discharge plasma can occur both ahead of the shock wave front in the region of low density and behind the front of the shock wave in the flow [5], as photo images of the discharge show. The surface discharges, in addition, can run along U-shaped channels, which include the line of surface intersection with front of the initial shock wave (see figure 3). The volume energy input into the gas is realized in front of the shock wave in the first series of experiments. The volume energy input realizes in a narrow region in
front of the shock wave front and/or in the flow behind it in the second series of experiments. The waveforms of discharge electric current in the experiments 2 a, b, c, d are rather different.

![Image of discharge during interaction with planar shock wave front outside the discharge volume (a); and the scheme of arrangement of U-shaped channels of the surface discharges (b).](image1)

**Figure 3.** The photo image of the discharge during interaction with the planar shock wave front outside the discharge volume (a); and the scheme of arrangement of U-shaped channels of the surface discharges (b). The optical axis of the photo camera is inclined to the surface discharge plane at a small angle. The arrow indicates the direction of movement of the plane shock wave.

![Graph of X-t diagram of the motion of discontinuities after discharge.](image2)

**Figure 4 X-t diagram of the motion of discontinuities after discharge.**

High-speed shadowgraphy showed the peculiarities of the motion of shock-wave configurations after discharge. In the first series of experiments, gas-dynamic discontinuities break down on the left boundary of the plasma volume containing the shock wave front (airflow - discharge plasma), and on the right boundary (discharge plasma - quiescent air) (fig. 2 b). When the initial plane shock wave breaks down, two shock waves and a contact surface are formed. Shock wave, a contact surface and a rarefaction wave generate on the plasma - quiescent air boundary. One of the formed shock waves moves to the right along the region of the relaxing plasma, compressing it and leading to long afterglow [7]. The narrow area near the shock wave front continues to radiate after the termination of the discharge current, and the afterglow duration depends on the experimental conditions and may exceed 2 μs. Surface discharges initiate shock waves moving in the direction transverse to the front of the initial shock wave and affecting the structure of the flow. The shock-wave configuration changes with time because of the motion and interaction of all waves with each other. The sequence of shadow images
after the discharge are shown in figure 2 e (Mach number of shock wave 2.2, $x_0 = -7$ mm). In this case, the objects formed after the discontinuities breakdowns are concentrated in a narrow region and form the shock-wave configuration described in [8]. For the conditions of this experiment, the average velocity of the right boundary of the shock-wave configuration (shock wave S1) is about 800 m/s in the first 20 microseconds. It is higher than the velocity of the initial shock wave. The velocity of the contact surface (CD) is ~ 420 m/s. The left boundary of the shock-wave configuration (shock wave S2) moves in the direction opposite to the flow, at a velocity of ~ 110 m/s. Figure 4 shows the $X - t$ diagram of the motion of discontinuities after discharge at Mach number of initial shock wave 4.2, $x_0 = -13$ mm ($X = x - x_0$).

Points denote the experimental values obtained by processing of images of high-speed shadow visualization. The lines indicate the results of the numerical calculation (see paragraph 4).

In the second series of experiments, when the shock wave front is beyond the discharge gap volume, the structure of the discharge glow and the structure of the shock-wave configuration after discharge are different in the cases: 1) $0 < x_0 \leq 7$ mm, 2) $7 < x_0 \leq 15$ mm, 3) $x_0 > 15$ mm. In the first case, the discharge current occurs along the shock wave and in front of shock wave; the shock-wave configuration is close to that realized in the first series of experiments. In the second case the volume energy input zone is narrow (practically the plane), and the surface discharges are stretched into U-shaped channels, enveloping the initial shock wave front (figure 2 e, figure 3). Two shock waves moving in opposite directions and two contact surfaces bounding the gas region heated by the discharge are formed in the volume (figure 2 f, Mach number of shock wave 2.2, $x_0 = 8$ mm). Surface discharges generate shock waves in the flow and near the front of the shock wave. In the third case, discharges are initiated only in the flow, without interacting with the front of the shock wave (figure 2 d).

4. Numerical Simulation

The dynamics of the gas flow discontinuities after pulse ionization of a space in front of a flat shock wave was studied numerically. The fast energy release in front of the shock wave changes the gas parameters in this area and breaks the Rankine-Hugoniot relations at the initial shock wave. As a result, the initial shock wave breaks down into three discontinuities: two shock waves and a contact discontinuity between them. This structure corresponds to the classical Riemann problem solution [8]. At the other boundary of the energy input, a shock wave, a contact surface and a rarefaction wave are formed.

The numerical simulation of the decay of the gas-dynamic discontinuity in the one-dimensional calculation was realized. The initial temperature was 300 K, and the initial density of air corresponded to the experimental conditions. The system of Euler equations was solved using the second-order Godunov method [10]. At the initial instant, three regions of the gas with different values of gas dynamic parameters were specified at the boundaries of these regions. The conditions of discontinuity decay were created including the energy input region in front of the shock wave, stationary air on the right of it at the initial experimental conditions, and the region on the left of the shock front with parameters of shock-compressed air in the airflow behind the shock wave. The energy input varied depending on the size of the energy input region. The adiabatic exponent for air was assumed to be constant 1.4. The Mach number of the shock wave varied in the limits 1.9-4.5.

Figure 4 shows the comparison results of the numerical simulation, which corresponds to 40% part of the discharge’s energy converting to the instant heating (Mach number of shock wave 4.2, $x_0 = -13$ mm) with the experimental data (positions of discontinuities at different time moments). The $X - t$ diagram of the discontinuities motion shows that the results of 1D numerical simulation coincides with the experimental results within 7-10 μs after the discharge.

5. Conclusions

Digital films of the high speed flow with combined discharge of nanosecond duration were obtained and analyzed when interacting it with a plane shock wave in the channel of discharge chamber. High-speed shadow recording of the flow field evolution after the discharge initiating was carried out with l
microsecond exposition. The dependence of the type of gas dynamic discontinuity breakdown on the initial position of the shock front is recognized.

A one-dimensional numerical simulation of the discontinuity breakdown at the front of a plane shock interacting with volume discharge is carried out. The experimental data of the discontinuity motion taken from digital films are compared with the calculated data; the discharge energy rate converted into the internal energy of the gas at the stage of the discharge electric current is determined in different experimental conditions.

The realization of various types of energy input for modification of flow patterns can be used in technologies of high-speed flow control.

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