Features of the interaction of shock waves with regions of a gas-discharge plasma of different structure

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Abstract. The work considers the possibility of influencing supersonic flows and shock-wave configurations by ionizing the propagation medium or flow around by creating a low-current gas discharge of different configurations. The experimental setup is a shock tube with a connected square working chamber with built-in electrodes to create a glow gas discharge of different intensity and uniformity. The process of the passage of a shock wave created in a shock tube through a region of a pre-arranged gas-discharge plasma having a uniform structure or stratified with ionization inhomogeneities of different scale is investigated. The formation of a new shock-wave configuration during the interaction of a shock wave with an ionized medium, as well as a strong distortion of the waveform up to its complete destruction during interaction with ionization-unstable plasma, has been found.

1. Introduction
The work is aimed at exploring the possibility of change, and thus control of strong shock waves up to completely destroying of them. The formulation of this problem in the modern aerodynamic field of science is relevant and in demand. In the work to influence on shock waves by changing the characteristics of the propagation medium, namely, by creating a region of a gas-discharge plasma is proposed. In [1], it was shown that the degree of nonequilibrium of the incoming on body ionized supersonic flow strongly affects the position of the bow shock wave until partially or completely destroying of it. In a number of works, when a shock wave passed through a region of a weakly ionized gas, splitting of a shock wave [2, 3] or the creation of complex gas-dynamic structures [4] were observed. This paper discusses the process of propagation of a strong shock wave (Mach number 6) in the afterglow region of a glow gas discharge with different intensity and structure. For this purpose, a diffuse or ionization unstable discharge with strata of different scale in the impact zone on the wave propagation path is organized. As a result, the shock wave propagates over the region of a homogeneous highly nonequilibrium plasma or over a medium with a layered structure with a higher degree of ionization and the temperature of electrons in the layers. The impact mechanism can be either plasma due to a change in the ratio of specific heats $\gamma$ of ionized regions [5], or thermal due to heating of the heavy component of the medium in these regions during thermal exchange with electrons [6], may be both.

2. Experiment arrangement
The experimental working chamber is a square channel connected to the end of a circular shock tube in which a shock wave is created, which then enters the working chamber. To organize the region of
gas-discharge plasma, pin electrodes to which voltage is applied are mounted in the upper and lower walls of the chamber. The magnitude of the gas-discharge current varies by the magnitude of the applied voltage and load. The height of the gas discharge zone is 5 cm, the width can vary depending on the method of organizing the discharge from 1 cm to 8 cm. The working gas for the propagation of a shock wave is xenon or air. To compare the degree of impact of the gas discharge region on the shape, intensity and speed of propagation of a shock wave, oscillograms of static pressure before and after impact area were fixed. To this end, the special piezoelectric sensors are mounted in the channel walls, located at a certain distance from each other, two before and two after the discharge zone. The current-voltage characteristics of the discharge are investigated, and the form of the shock wave passing through the impact region is recorded by visualization of the flow picture in this region by Schlieren method with a high-speed multi-frame shooting. The time of passage of the shock wave along the observation region is 60 μs, the exposure time of frames is 500 ns, the time between frames is 10–15 μs. The scheme of the experimental installation [7] with the gas discharge organization systems and the visualizing Schlieren system is shown in Figure 1. The interaction of a shock wave with a plasma region of different structure is considered by creating a gas discharge of several types.

3. Applying of external electrical field

In this case, a voltage of up to 600 V was applied to the electrodes prior to the arrival of the shock wave, thereby creating an electric field in the impact area on the wave path without first igniting the discharge. It was assumed that the closure of the gas-discharge current will occur on the shock wave as an ionized medium, thereby acting on it. It was found that the gas-discharge current is not closed by the shock wave, it is closed some time later (about 30 μs) after the shock wave enters the voltage application zone. The Schlieren photographs of the flow in Figure 2 clearly show the primary discharge of the circuit, which initiates the ignition of the gas discharge and moves behind the shock wave at a slower speed. After the release of the initiating discharge from the zone of application of the electric field, a homogeneous gas discharge continues to burn in the discharge zone. The intensity of the initiating discharge increases with increasing magnitude of the applied voltage, and therefore the gas-discharge current [8]. The structure of the discharge is shown in more detail in Figure 3. It can be seen that the discharge moves along the electrodes, a brighter thin channel passes in the center, and the discharge is turbulent on the flow axis.

Figure 1. Scheme of the experimental setup. 1, 2 - shock tube (1 - high pressure chamber, 2 - low pressure chamber), 3 – working chamber, 4 - cellophane diaphragm, 5 – gas discharge (and observation) zone, 6 – damper tank, 7 - Schlieren system, 8 – CCD camera, 9 – laser, 10 – wiring diagram of electrodes with a DC voltage source and load resistance, 11 – load resistance.
Figure 2. Shock wave passing through the impact zone.

Figure 3. Structure of the initial discharge.

4. Interaction with the uniform discharge zone

In this case, a uniform glow discharge at a current of 10-100 mA is ignited in the impact zone in advance before the arrival of the shock wave, the shock wave suppresses the discharge and spreads over the zone of the relaxing plasma. The discharge relaxation time is several ms, during the passage of the shock wave in the impact area (about 30-60 μs), the ionized medium of wave propagation does not have time to change. The discharge form is shown in Figure 4 (a). Figures 4 (b), (c), (d), (e) represent result form of the shock wave at different values of the gas-discharge current, which value is shown in the top of pictures. It can be seen that immediately after the shock wave enters the plasma region, a new shock-wave configuration is formed due to the formation of an additional gas-dynamic discontinuity, presumably, the contact surface. The shock wave becomes broadened, the broadening increases with increasing gas-discharge current. With an increase in the gas-discharge current in the range of 10-160 mA, the velocity of propagation of the shock wave over the plasma region also increases from 1.8 to 2.1 km / s [9].

Figure 4. Broadening of the shock wave.
5. Interaction with the ionization unstable discharge zone with large scale strata
In this series of experiments, before the arrival of a shock wave, an ionization unstable discharge is created in the impact zone with large-scale spherical ionization strata representing ionization waves [10] aligned along the gas-discharge current (about 5 strata per discharge length). These are areas with an increased ionization rate and electron temperature. As a result, a layered structure of the propagation medium is formed, that is, the alternation of regions with a higher and lower electron temperature, and as a consequence, a gas temperature. The alternation of layers occurs in the direction transverse to the propagation of the shock wave. With the passage of such a gas-discharge zone, both the broadening and distortion of the shock wave is observed, as can be seen from Figure 5. Here in figures (a), (b) and (c) the moments of the shock wave passing through the observation zone (at the entrance, in the center and at the exit) in the absence of the gas discharge. Figure 5 (d) demonstrates the shape of an ionization-unstable discharge with large strata. Such form of discharge is formed when the discharge current in the range of 100-200 mA. Figures 5 (e) and (f) show the results of the impact of such a discharge on the shape of the shock wave in the discharge zone (e) and after passing through zone (f). It is seen that the shape of both the wave and the contact surface is bent, resembling the shape of the strata, and becomes unstable. The distortion persists outside the discharge zone.

![Figure 5](image)

Figure 5. Distortion of the shock wave.

6. Interaction with the ionization unstable discharge zone with small scale strata
In this case, an ionization unstable discharge with small-scale ionization strata (of the order of 20 strata per discharge length) is created in the impact zone, therefore with a small-scale layered structure of the propagation environment. The results of these experiments are shown in Figure 6. Figure 6 (a) shows the shape of the discharge, this form is observed at currents of 300-400 mA. Figures 6 (b) and (c) show the entrance of a shock wave into the discharge zone and its gradual broadening. Directly in the discharge area, a strong attenuation of the shock-wave configuration occurs, which becomes almost indistinguishable in the Schlieren pattern (Figure 6 (d)). The position of the wave
discontinuities is shown in figure (d) by arrows. In the area behind the discharge zone along the shock wave itself is not observed, this moment of flow is shown in Figure 6 (e).

![Figure 6](image)

**Figure 6.** Attenuation and disappearance of the shock wave.

Thus, it has been shown that ionization of the medium of propagation of a shock wave leads to the formation of a new shock-wave configuration, including a contact discontinuity. Large-scale temperature inhomogeneities of the medium lead to the curvature and instability of the shock configuration, small-scale temperature inhomogeneities can lead to the destruction of both the shock wave and the contact surface. It means that the most effective impact on shock wave is when energy is invested to small-scale temperature inhomogeneities of the propagation environment. The observed phenomena can be used to control supersonic flows and shock-wave configurations, as well as mixing processes.

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