Impact of homogeneous and ionization unstable glow discharge plasma on a shock wave in air

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Abstract. The work is aimed at exploring the possibility of control of strong shock waves up to their completely destruction. The impact on shock waves by creating a region of gas-discharge plasma in propagation media is proposed. A diffuse or ionization unstable discharge with the ionization strata of different scale on the path of a shock wave propagation is organized. As a result, the shock wave propagates over the region of homogeneous highly non-equilibrium plasma or over the medium of layered structure with higher degree of ionization and electron temperature in the layers. Numerical simulation of the propagation of a shock wave over the region of energy impact was carried out on the basis of the systems of Euler and Navier-Stokes equations with the flow parameters obtained in the experiment. The homogeneous plasma region was simulated by a rarefied gas region with increased temperature and constant pressure. The area formed by the ionization unstable discharge was simulated by a thermally stratified gas area. The strong influence of the ionization of the propagation medium on the transformation of the shock wave with the formation of a new shock wave configuration is shown. Stratification of the medium leads to a distortion of this configuration up to complete destruction of it.

Introduction

The task of controlling supersonic flows by non-mechanical methods with the aim of changing the shape and intensity of shock-wave configurations up to their complete distortion, as well as changing the aerodynamic characteristics of poorly streamlined bodies is widely demanded in modern aerodynamics. Non-mechanical control methods have a significantly better temporal resolution compared to currently used mechanical methods. This problem is solved by a number of authors using gas discharges of various types and structure which are organized in a flow [1-5] or near a streamlined surface [6-7].

This paper proposes to influence the shock waves, their shape, intensity and speed of propagation by creating local ionized zones along the path of their propagation with the help of a gas discharge. The aim of the study is to choose the most optimal configuration of impact. For this purpose, the interaction of a shock wave (SW) with the Mach number 5-6 with the region of a glow gas discharge of different intensity of the discharge current and different types of ionization stability is studied. The impact mechanism can be characterized as thermal - due to heating the heavy component of the medium in
these regions during the thermal exchange with electrons. In addition, it can be influenced by plasma effects connected with non-equilibrium processes.

1. Experiment arrangement

The studies are carried out in a straight channel of square section, which is a continuation of a circular shock tube, in which a strong SW is formed, and then enters the working chamber. The scheme of the experimental setup is shown in Fig. 1. The shock tube includes a high pressure chamber (1), a low pressure chamber (2) and a measuring section (3) for flow checking. The cross-section of the shock tube is inscribed in a square section of the working chamber (7), as shown in the diagram (section A-A). The working chamber is separated from the shock tube by a Dacron diaphragm, which allows avoiding transients with the formation of a complex shock-wave structure [8]. It also allows creating a reduced air pressure (7 Torr) in the working chamber, which makes it possible to organize both a uniform diffuse discharge and an ionization unstable one. The working gas is air, the initial pressure in the low-pressure chamber is 20 Torr at room temperature, the Mach number of the shock wave is \( M = 6 \).

![Figure 1. Installation scheme: 1 - high pressure chamber; 2 - low pressure chamber; 3 - measuring section; 4 - electrodes; 5 - optical window; 6 - discharge zone; 7 - working chamber; 8 - bellows; 9 - damper chamber; 10 - a cross section of the working chamber; 11 - a cross section of a shock tube with diameter 50 mm; 12 - Dacron diaphragm; 13 - piezo sensors.](image)

The discharge current is organized across the flow direction. The shape of the discharge was changed by changing the intensity of the gas-discharge current, which was regulated by the value of the load resistance. Depending on the magnitude of the gas-discharge current, it is possible to create a uniformly ionized area of impact or a stratified one with ionization strata of various scales. The width of the discharge zone varied within 4–8 cm. The gas discharge was ignited in advance before the shock wave arrived at the zone of action. The shock wave suppresses the discharge and propagates through the afterglow zone. The time of passage of the discharge zone is 30–40 \( \mu \)s, which is two orders of magnitude shorter than the plasma relaxation time. This suggests that the ionization parameters in the impact zone during the passage of the shock wave are almost the same as in the active discharge zone. The direction of propagation of the shock wave in the impact zone is indicated in Fig. 1 by an arrow.
The diagnostics of the flow was carried out by visualizing gas-dynamic discontinuities, namely, density gradients, and their evolution by high-speed multi-frame schlieren system through the optical windows (5 in Fig. 1). In addition, the time taken by SW for passing between the measuring marks before and after the impact zone (to determine SW propagation velocity) is recorded. To this end, two sensors before and two after of the impact zone were installed in the side walls of the channel at the same distance from each other (13), which also make it possible to measure the static pressure in the working chamber.

Photo of working chamber is shown in Fig. 2. Here one can see a straight channel, a discharge zone with electrodes, optical windows, located in the impact area on the side walls of the chamber, as well as piezo sensors, mounted in front of the discharge zone and after it.

![Figure 2. Photograph of the working chamber with the impact zone](image)

2. Interaction of SW with the homogeneous diffuse discharge region
At the gas-discharge current of 100-200 mA, a homogeneous discharge is observed in the impact area (Fig. 3a). When SW enters the impact region, the formation of a new shock-wave configuration (Fig. 3c) is observed; SW is broadened in comparison with the original its form as shown in Fig. 3b. The width of the new formation depends on the magnitude of the gas-discharge current and persists when passing through the impact zone. It was also found an increase in the velocity of SW propagation in the gas-discharge zone with increasing the discharge current intensity.

Numerical simulation of this flow by solving the 2D Riemann problem showed that the observed broadening of SW is associated with the formation of a shock structure consisting of SW and contact discontinuity (CD) moving to the initial SW direction [9]. The numerical density field is shown in Fig. 3d. One can see a good agreement with the experimental data. In the calculated pressure field, this discontinuity is absent, which indicates the formation of a contact surface.
3. Interaction of SW with large-scale ionization strata

Unboundedness of the gas discharge in the direction of the flow allows organizing ionization-unstable discharge [10] with ionization strata of different scale, representing the areas of increased ionization rate, temperature and electron concentration [11]. When a gas-discharge current is in the range of 200-300 mA, large-scale strata are formed in the discharge zone, lining up along the current line, 5-7 strata per discharge length. Figure 4a presents a photograph of such discharge. The discharge region in this case is a layered structure with different degrees of ionization and temperature of the electron and gas components. As a result, an impact zone with longitudinal large-scale ionization and temperature inhomogeneities is formed.

When SW passes through the area of such a discharge, its front is distorted and bends, repeating the shape of the discharge area (Fig. 4b). Note that an additional gas-dynamic discontinuity is also formed behind the SW, repeating the waveform. Coming out from the impact zone, SW and CD retain distorted and of unstable shape (Fig. 4c).

Simulations of the flow based on numerical solving of the Euler and Navier-Stokes systems of equations assuming the temperature inhomogeneities of such scale in the region of SW propagation are in a good accordance with the experiments (Fig. 4d). It can be seen that the presence of temperature
inhomogeneities of the medium causes the development of vortices and instabilities which leads to the distortion of SW and CD.

4. **Passage of SW through the region of small-scale ionization strata**

Figure 5a presents a photograph of the discharge with small-scale ionization strata up to 20 strata over the discharge length. Such a discharge structure is observed at the gas-discharge current in the range of 300-400 mA and creates a layered structure of the medium with small-scale temperature inhomogeneities in the impact zone. When SW enters the impact zone, it immediately starts to distort (Fig. 5b). In addition to broadening, there is a strong weakening of the density gradients in the discharge zone, as result the gasdynamic discontinuities becomes almost indistinguishable in the Schlieren image (Fig. 3c). Upon leaving the impact zone, SW is not observed, it is completely destroyed [8].

![Figure 5](image)

**Figure 5.** a) Photograph of an ionization-unstable discharge with small-scale strata; b) SW distortion when entering the discharge zone; c) Weakening the shock-wave configuration in the discharge zone; d) Computational density field, interaction of SW with small-scale temperature inhomogeneities

Numerical calculations also showed that the deposition of energy in small-scale temperature inhomogeneities in front of SW propagation leads to the destruction of the SW due to the generation of multipoint shear layer instabilities (Fig. 5d, $M = 2$).

5. **Conclusions**

1. The interaction of a plane shock wave with a region of stable and ionization unstable discharge characterized by strata of different scales has been investigated.
2. It was shown that the discharge has a strong effect on the shape and stability of a shock wave up to its complete destruction.
3. During the shock wave interaction with an ionized zone a new shock-wave configuration is formed including the shock wave and contact discontinuity which have been obtained experimentally; their formation has been confirmed numerically.
4. It was shown that the most effective impact on shock wave is when energy is dislocated in small-scale temperature inhomogeneities of the medium.
5. Numerical simulation of the flow under the assumption of temperature inhomogeneities corresponding to the experimental scale of strata has shown a good agreement with the experiments.

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