# Passage of a Shock Wave through the Region of Ionization Instability of Gas Discharge Plasma

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*Abstract:* - The article refers to the field of supersonic flow control via external energy deposition. Passing a strong shock wave (M=5-6) through the region of pre-formed ionization instability in gas discharge plasma has been studied experimentally and numerically. In the experiments the ionization spherical strata have been obtained arising in the gas discharge region due to the development of the ionization instability in air. As a result of the interaction of an initially plane shock wave with the plasma region of ionization instability the formation of new complicated shock-wave configurations was obtained the shape of which changed from smooth to gear. These configurations were shown to acquire an unstable character. Numerical simulations were carried out on the basis of the Euler system of equations with the parameters corresponding to the experimental conditions with the use of the complex conservative difference schemes. The stratified energy source was modelled by a set of thermal layers with varying characteristics. Changes in the physic-chemical properties of the medium were described by varying the adiabatic index. Stratified shock-wave structures consisting of modified wavy shock-wave and contact discontinuities have been obtained as a result of the interaction of the shock wave with the region of ionization instability. Generation of the Richtmyer-Meshkov instabilities has been obtained on the thermal strata in the vicinity of the shock wave front curvatures which confirmed the unstable character of the shock wave front. Comparison of the obtained experimental and numerical shock front evolution showed a good agreement. Results of the study can be used to control of high speed flows and shock-wave configurations, as well as mixing processes.

*Key-Words:* - Shock wave, glow gas discharge, ionization instability, stratified energy source, Richtmyer-Meshkov instability, complex conservative difference scheme

# 1 Introduction

The influence of heated areas on the shock wave as well as the impact of an energy source located in front of an aerodynamic body on supersonic flow over it currently is an extensive field of research with applications to the class of problems of supersonic flow control [1-4]. Different type of energy deposition is used for these purposes, microwave [5], laser [6] and gas discharge [7].

In [7] the possibility of both purely plasma action via the change in the degree of non-equilibrium of the incoming flow and magneto-hydrodynamic action via an additional external magnetic field was obtained. The impact of plasma regions on the structure and dynamics of shock waves was studied in [8, 9]. The possibility of controlling shock-wave configurations by creating local plasma gas-discharge areas in front of the streamlined body or directly on the surface of the body was shown. The effect not only on the position of the bow shock wave but also on the aerodynamic drag and lift forces was demonstrated.

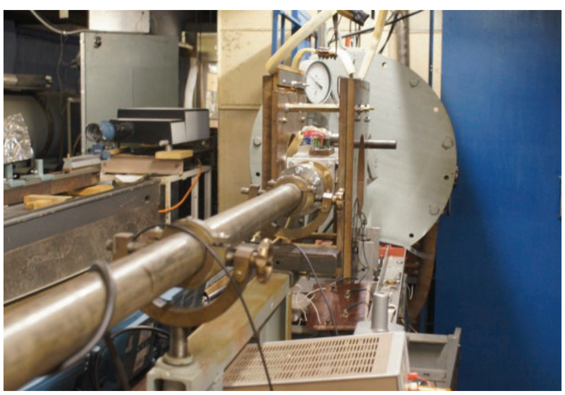


Fig.1. Shock tube with working chamber

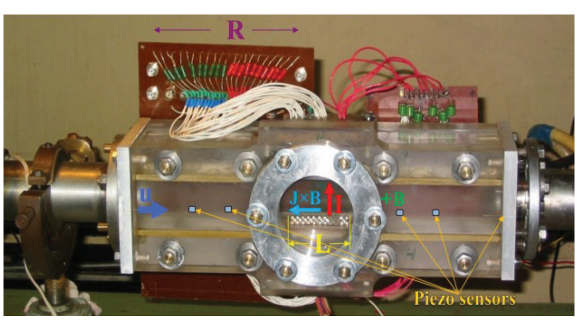



Fig.2. Working chamber

As a result of the interaction a moving shock-wave structure consisting of two discontinuities, shock wave and contact discontinuity whose convexity is directed towards the motion of the initial wave was obtained. The problem of passing a plane shock wave through a weakly ionized homogeneous plasma region in a rectangular channel was considered experimentally and numerically in [10].

In [11] the experimental modelling of a similar problem of the decay of an arbitrary discontinuity in the conditions of fast energy deposition with the increased pressure in the gas-discharge region was carried out. The shock-wave structure consisting of two shock waves separated by a contact discontinuity was obtained there.

Modification of a Mach 2 supersonic flow over a plate under the action of direct current plasma discharge was considered in [12]. The effect of the plasma presence on shock wave strength and on the sound speed and specific heat ratio of the initial gas was researched. The disappearance of the reflected shock wave from the horizontal wall due to the stratified structure of specially created filaments with the use of quasi-direct-current electrical discharge is obtained in [13].

In this paper the initially plane shock wave propagation throw the plasma area of ionization instability is studied experimentally and numerically. The stratified plasma region of changing mode has been obtained experimentally with the use of an electrical glow discharge in air in a working chamber joined with a shock tube. Investigations have been conducted of the interaction of a plane shock wave with the obtained plasma area of ionization instability.

Simulations are carried out on the basis of the two-dimensional Riemann problem of the decay of an arbitrary discontinuity taking into account the influence of the walls of the working chamber. The plasma instability region was modeled via a stratified energy source which consists of rarefied gas layers of high temperature and constant pressure. Non-equilibrium processes in the gas discharge region are modeled by an effective ratio of specific heats $\gamma$.

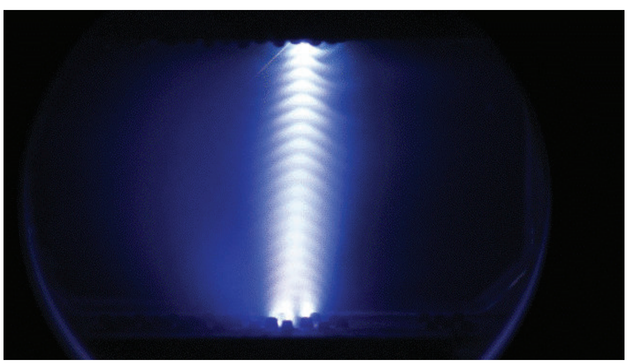
Results of the study can be used to control of high speed flows and shock-wave configurations, as well as mixing processes.

## 2 Experimental Research

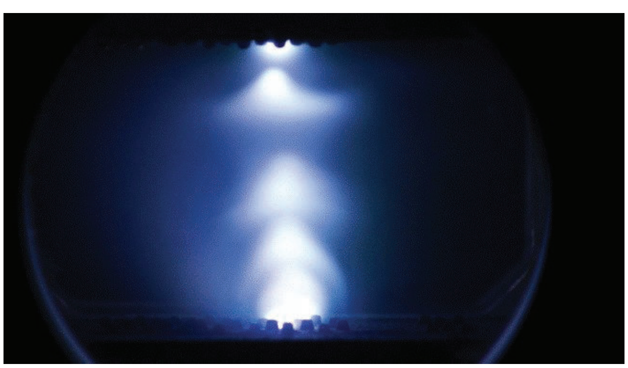
### 2.1 Experimental installation

The studies are conducted in a direct MHD channel with a square cross-section coupled with a circular shock tube in which the formation of shock waves of different intensity occurs. Photo of the shock tube with the working chamber is shown in Fig.1. In Fig.2 the working chamber of square section is presented.

Gas discharge with current $I$ is organized in the zone of action in the working chamber with the help of special low current circuits connected to the pin electrodes built into the upper and lower walls of the working chamber. The pin electrode area is 8x2 cm and includes 34 pin electrodes on the top wall and the same number on the bottom one. Each pin electrode has a load resistance R=3 Ohms. The length of the impact zone can vary from 1 cm to 8 cm depending on the number of connected pin electrodes. The intensity of the gas discharge can vary over a wide range of parameters. The working medium of the working chamber is air.



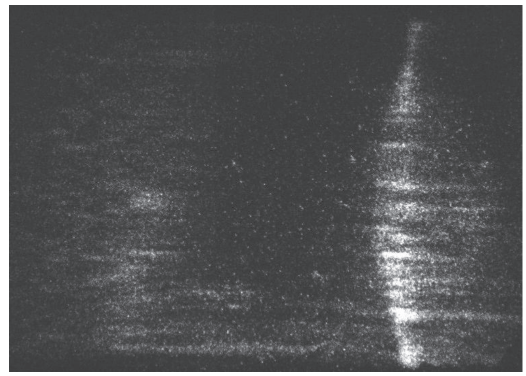
a)



b)

Fig.3. a), b) - Examples of ionization-unstable discharge

To visualize the impact zone during the passage of a shock wave a Schlieren system with illumination from a non-stop laser with a wavelength of 532 nm is used. The receiving part of the system is a high-speed SSD camera which allows obtaining up to 6 frames with a duty cycle and exposure time up to tens of nanoseconds. It allows considering the whole process of passing the shock wave through the impact zone.



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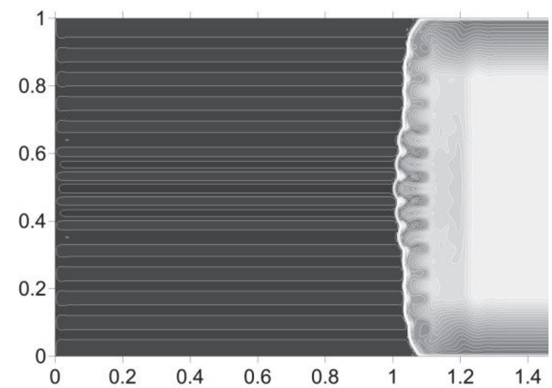


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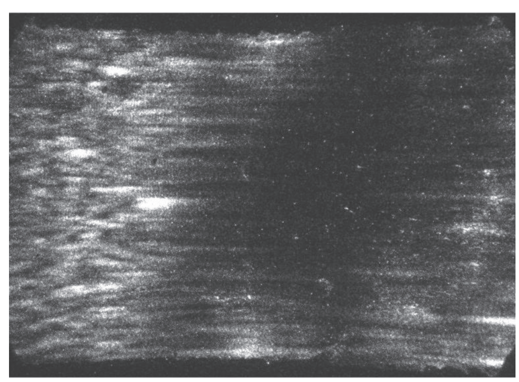


c)

Fig.4. Process of passing the shock wave through the region of ionization-unstable plasma:
a), c) - experiment, b) – calculations

## 2.2 Experimental results

At the gas-discharge current $I$~200-300 mA spherical strata of different configurations have been observed in the gas discharge region which are the result of the development of the ionization instability.

In this work for impact on the shock wave the ionization-unstable plasma was organized by creating a stratified gas discharge. Strata in the discharge are ionizing waves moving from the cathode to the anode [14]. They arise due to periodic changes in the electron density caused by alternating predominance of the birth or death of electrons in different areas of the discharge. The condition of occurrence of strata depends on the type of gas, the pressure and the gas discharge current.

It should be noted that the occurrence of ionization strata is typical mainly for gas discharges in inert gases. In this experiment, the pressure and the current value are chosen so that there is a rare phenomenon – the emergence of the spherical strata in the molecular gas, namely in the discharge in air. Examples of the ionization-unstable discharge are shown in Fig.3.

In Fig.4a it can be seen that the distortion of the shock wave occurs already at the entrance of the discharge zone, the central part of the wave being wider than its peripheral parts. As the shock wave propagates through the discharge zone the broadening is increasing and the shock wave becomes vaguer. At the exit from the strata zone (dark region in the Schlieren image) the shock wave is completely disappearing, as can be seen in Fig.4c. In a number of experiments the shock wave was not quite disappearing when passing throw the stratified zone but a shape of its front was distorted (Fig.5a). Figs. 4b and 5b will be explained in sub-Section 3.2.

# 3 Numerical simulations

## 3.1 Statement of the problem

The simulations of interaction of an initially plane shock wave with the stratified plasma region are based on the Euler system of equations:

$$\mathbf{U}_t + \mathbf{F}_x + \mathbf{G}_y = \mathbf{0}, \qquad (1)$$

$$\mathbf{U} = (\rho, \rho u, \rho v, E)^T,$$

$$\mathbf{F} = (\rho u, p + \rho u^2, \rho uv, u(E+p))^T,$$

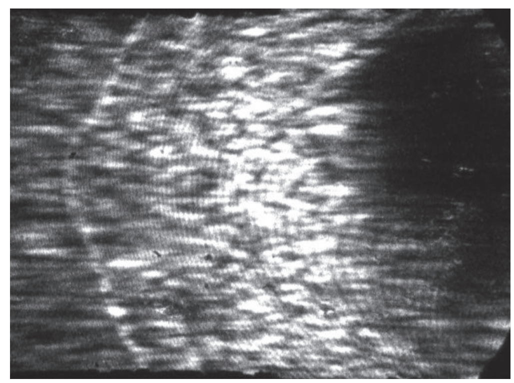
$$\mathbf{G} = (\rho v, \rho uv, p + \rho v^2, v(E+p))^T,$$

$$E = \rho(\varepsilon + 0.5(u^2 + v^2)).$$

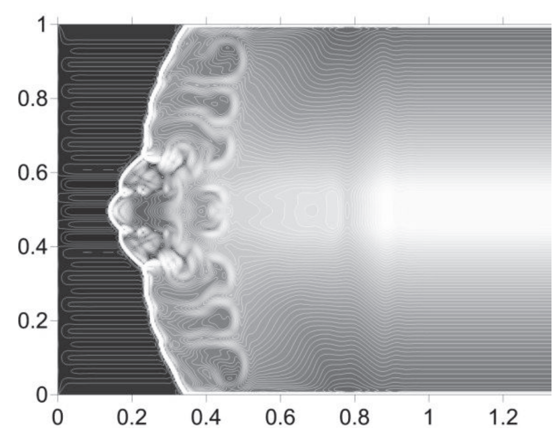
The state equation for a perfect gas is used:

$$\varepsilon = p/(\rho(\gamma - 1)).$$

Here $\rho$, $p$, $u$, $v$ are the gas density, pressure and velocity $x$- and $y$-components, $\varepsilon$ is the specific internal energy. Gas media with the ratio of specific heats $\gamma$=1.2 is considered. This value of $\gamma$ was shown to provide better curvature of a shock wave front during its passage throw the homogeneous gas discharge plasma [10]. As obtained in [12], such a value of $\gamma$ may correspond to the degree of ionization of the gas medium of 0.00015 and the degree of non-equilibrium of 0.015.



a)




b)

Fig.5. Distortion of the shock wave passing through the ionized unstable plasma:
a) - experiment, b) - calculations

The region of ionization-instable plasma was modeled by a stationary stratified region of rarefied gas located inside the zone of the discharge action at some distance in front of the shock wave. The vertical size of the plasma area coincided with the width of the working chamber. To simulate the experiment, the influence of the horizontal walls was taken into account. It was believed that the walls do not have time to warm up and remain cold and the parameters on them are equal to the initial parameters of the gas. In addition, it was suggested that the gas is slowed down at the walls of the chamber (adhesion conditions were used). The effect of the horizontal walls determines two-dimensional nature of the interaction. On the right boundary of the computational domain no reflection conditions were used.

The stratified energy source was modeled as a set of heated layers with a gas density smaller than in initial undisturbed flow $\rho_i=\alpha_{\rho i}\rho_\infty$, $\alpha_{\rho i}<1$ (index $\infty$ refers to the parameters of undisturbed flow). The values of pressure inside these layers were set equal to the initial parameters of the flow inside the working chamber. At the same time, the temperature inside the layers was increased compared to the initial temperature of the gas, $T_i=\alpha_{\rho i}^{-1}T_\infty$.

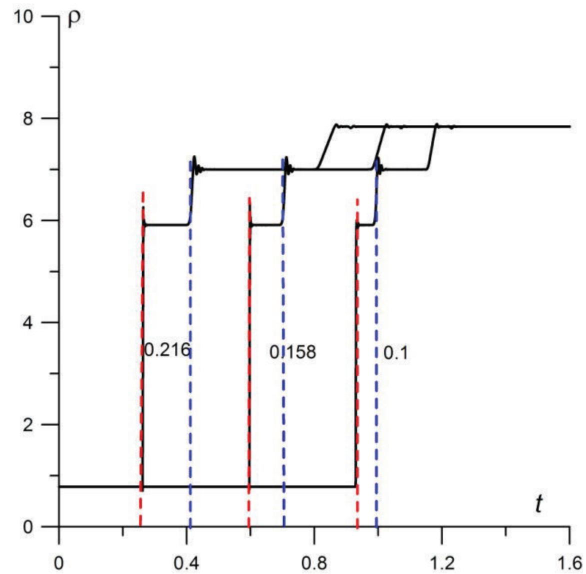
Thus, here the heat model of stratified plasma region is suggested and the possible heat effects are studied. Normalizing values for density and pressure are $\rho_n$=1.293 kg/m$^3$ and $p_n=1.01325\times10^5$ Pa, accordingly. So the dimensionless values $p_\infty=1$ and $\rho_\infty=1$ refer to the normal conditions in air.

The problem is solved in the dimensionless variables. Complex conservative schemes are used in the simulations. Details of the schemes construction together with numerous test variants have been described in [15]. Staggered Cartesian difference grid with the space steps equal to 0.001 and 0.002 (1000 or 500 points per the working chamber width) is used.

## 3.2 Numerical results

The shock wave of Mach number M=4.98 moves to the left and interacts with the plasma region. For the homogeneous discharge plasma area this problem has been researched in [10]. It was shown that when the front boundary of the thermal region interacts with the shock wave a new shock-wave configuration occurs which is described in one-dimensional approach by the solution of the Riemann problem similar to that given in [16].

From the centre of the interaction to the left a shock wave and a contact discontinuity are moving and a rarefaction wave is moving to the right. In Fig.6a the comparison is presented for

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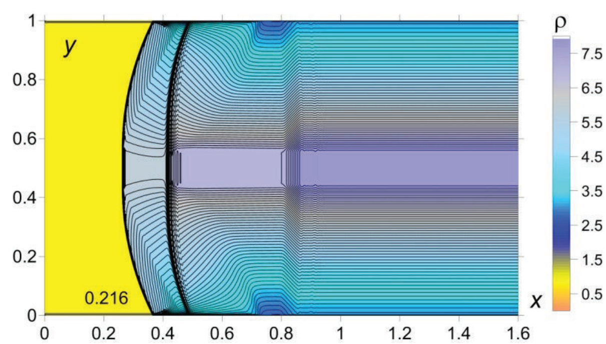
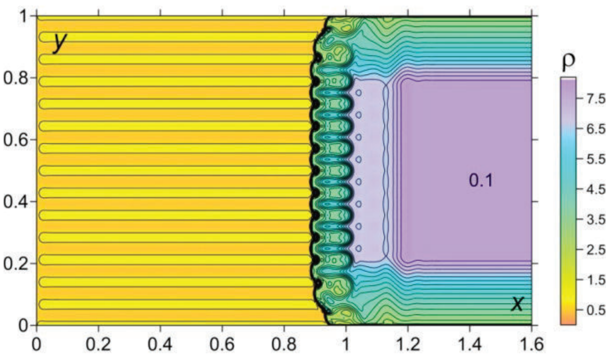



b)

Fig.6. a) - Dynamics of the quasi-one-dimensional Riemann problem solution on the axis of symmetry: homogeneous energy source, $\gamma$=1.2, $\alpha_\rho$=0.786; b) – density isolines for $t$=0.216.

the calculation results on the axis of symmetry (*black solid* lines) with the analytical ones obtained for the one-dimensional Riemann problem describing the interaction of a plane shock wave with a hot (homogeneous) region. *Dashed red* and *blue* lines denote the locations of shock wave and contact discontinuity fronts from the analytical solution. The initial shock wave $x$-coordinate is 1.5 and the energy source $x$-coordinate is 1.4. Arising 2D shock structure is presented in Fig.6b.

In the case of a stratified energy source the arising shock-contact structure is more complicated. Dynamics of such shock-contact structure development is presented in Fig.7. Here the time values are indicated, the dimensionless time value 0.058 corresponds to time interval 10μs. The energy source is modelled by the amount of heat layers $n_l$=14, with equal rarefaction factors $\alpha_{\rho i}$=0.5 and the gaps between the layers equal to $0.5l_i$ , where $l_i$ is the width of the $i$ heat layer. The initial shock wave $x$-coordinate is 1.5 and the energy source $x$-coordinate is 1.4.

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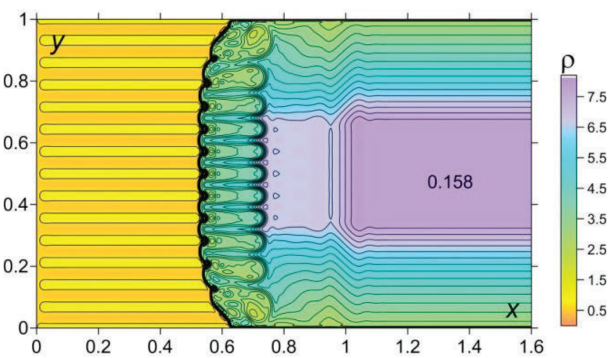


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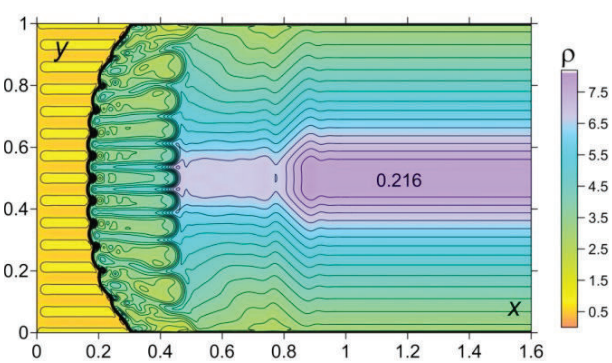



c)

Fig.7. Dynamics of shock-contact structure passing through the region of ionisation instability modelled by stratified energy source, isolines of density: a) – $t$=0.1, b) – $t$=0.158, c) – $t$=0.216

It is seen that the shock-contact structure consists of the curved periodical shock wave front and the curved periodical contact discontinuity front, the horizontal sizes of this structure are in accordance in average with those obtained in [10] for the homogeneous plasma region (see Fig.8).

By changing the parameters of the heat layers in the stratified energy source the qualitative results explaining the phenomena which are taken place in the experiments have been obtained. The shock wave entrance into the instability area has been better described by the source with of $n_l$=15, with the centre value of the rarefaction factor $\alpha_{\rho 7}$=0.45, $\alpha_{\rho 6}$=$\alpha_{\rho 8}$=0.45, $\alpha_{\rho 5}$=$\alpha_{\rho 9}$=0.55 and the other $\alpha_{\rho i}$=0.7 (see Fig.4b).

In the experiments when the shock wave passes through ionization-unstable plasma an action of the gas discharge in addition to broadening can lead to changing the shape of the shock wave front. Qualitative results for this situation are better for the parameters of the stratified energy source: $n_l$=15, $\alpha_{\rho 7}$=0.45, $\alpha_{\rho 6}$=$\alpha_{\rho 8}$=0.45, and the other $\alpha_{\rho i}$=0.7 (see Fig.5b). Thus the results show that more rarified (and accordingly of the high temperature) strata are in the central part of the ionization instability near the axis of the flow symmetry and the difference in the gas temperature between the strata increases with time.

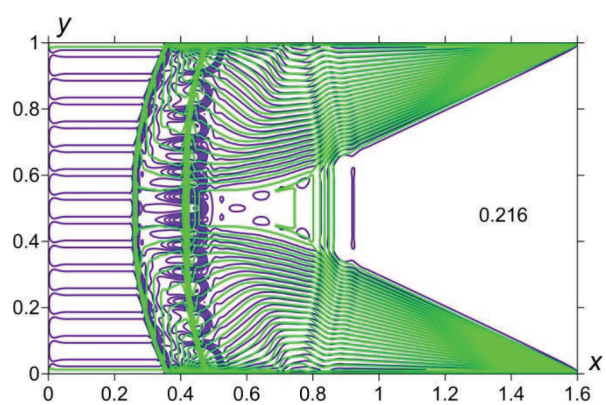
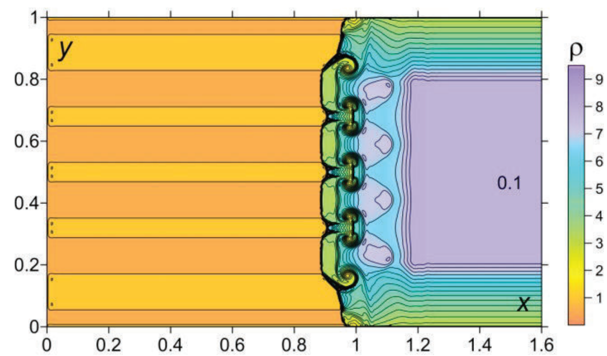
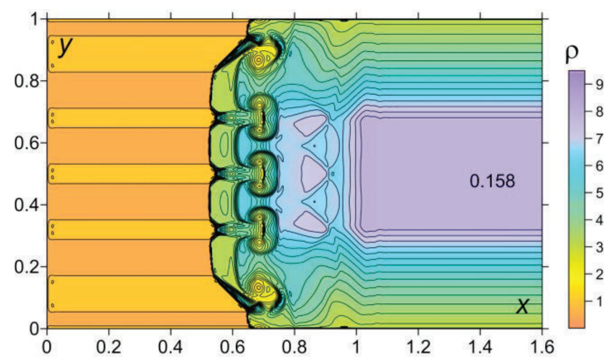



Fig.8. Comparison of shock-contact structures passing through the region of stratified (*violet,* $\alpha_{\rho i}$=0.786) and homogeneous (*green,* $\alpha_\rho$=0.786) energy sources, isolines of density, image overlay (precise boundary conditions on the right boundary)

Experiments show that the ionization instability can lead to instability of the shock wave front or its complete disappearance when leaving the impact zone. The numerical results showed the possibility of shear layer instability generation, in particular, the Richtmyer-Meshkov instability generation under the considered conditions. Generation of the Richtmyer-Meshkov instability in the problem of heated layer-bow shock interaction has been established in [17] in problems of the external energy deposition impact on the supersonic flow past a cylinder. Fig.9 demonstrates the origination of this type of instability for the stratified energy source-shock wave interaction. Here $n_l$=6 and all $\alpha_{\rho i}$=0.5.




a)

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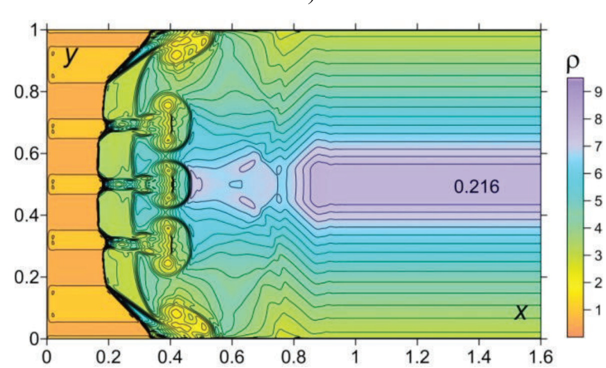


c)

Fig.9. Dynamics of generation of the Richtmyer-Meshkov instabilities accompanying interaction of shock wave with stratified energy source, isolines of density: a) – $t$=0.1, b) – $t$=0.158, c) – $t$=0.216

In a case when the shock wave velocity is smaller than sound speed in the heated layers in the stratified energy source ("subsonic" energy source) the shock wave front is weakened and undergoes the influence of shear layer instability. These factors lead to the blurring and disappearance of its front (Fig.10). In [13] the similar results have been obtained experimentally on disappearance of the reflected shock while interacting with flow region with alternating supersonic and subsonic layers.

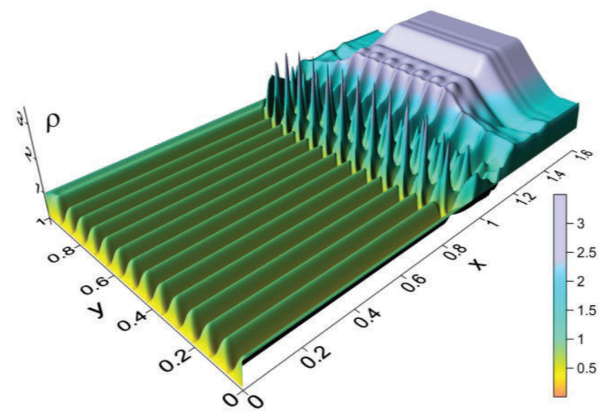


Fig.10. Disappearance of shock wave front dui to shear layer instability, "subsonic" stratified energy source: M=2, $\alpha_{\rho i}$=0.3, $t$=0.216

Thus, the obtained qualitative results show the heated stratified type of plasma media inside the region of ionization instability with more heating layers close to the axis of symmetry. In addition, the results indicate unstable character of the arising shock-contact structures.

## 4 Conclusion

The ionization instability has been obtained experimentally in air in an area of a glow gas discharge action. The unstable plasma region has been shown to consist of stratified plasma medium and has a changing structure. Numerical modeling was based on the heat assumptions.

The comparison of Schlieren images and calculated dynamics of the obtained complicated shock-contact structures showed layered by temperature nature of the ionization instability (with the maximum temperature layers dislocated in the centre of the working chamber). In addition, the tendency of the shock front to distort and to become of unstable character up to complete disappearance during the passage of the zone of ionization instability has been established.

In future it is planned to take into account the non-equilibrium character of the considered phenomena and introduce the code insert into the simulations for research the influence of chemical reactions.

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