Shock waves under nanosecond ionization

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Shock wave interaction with zone of instant (nanosecond-lasting) ionization in shock tube channel is a complicated non-stationary process. The research of quick energy release influence on parameters of supersonic gas flow is a very actual problem. This problem is closely linked with applied problems of laser physics, plasma chemistry, plasma aerodynamics [1]. The purpose of the present work is to investigate nanosecond- lasting volume and surface discharges in test camera of shock tube in the presence of different shock configurations and discharge glow analysis.

Non-stationary processes in shock tube gas flow are determined by interactions of discontinuities and gasdynamic perturbations with velocities range 10^2 -10^4 m/s. The range of characteristic gasdynamic time interval is ~ 10^{-5}-10^{-7} s. Energy input process realized in time interval t_e much smaller than characteristic time can be considered as “instant”. At the shock wave’s velocity ~10^3 m/s (shock wave Mach numbers of M = 2-6) the times should be no more than microseconds. At time $t_e > 10^{-6}$ s shock wave shift is comparable with characteristic scales of gas flow. In that case it is necessary to take into account gas flow configuration changes and thermal heating during time of energy input t_e. Thus, for adequate experimental simulation of impulse energy input in a segment of non-stationary gas flow with shock waves it is necessary to conduct homogenous ionization with nanosecond duration. Thus nanosecond-lasting volume discharge with pre-ionization [2,3] should be considered as instant energy input in gas flow with shock waves. Nanosecond-lasting surface discharge realizes instant energy deposition in gas near a wall (boundary layer).

Experimental researches

The realization of nanosecond process of gas flows’ pulse ionization with shock waves is implemented on the experimental setup UTRO-2 (fig. 1).The experimental setup consists of the shock tube with high-pressure chamber, diaphragm section and low-pressure chamber including special discharge section. Shock tube and discharge chamber have rectangular profile 48×24 mm. Flow gas is air and pumping gas is helium. Experiments were made in the air at pressure from 20 to 600 Torr. Mach numbers of a shock waves were M = 2-5; flow velocities from subsonic to 1600 m/s. Two side walls of the discharge chamber were the quarts plane glasses of 170 mm length.

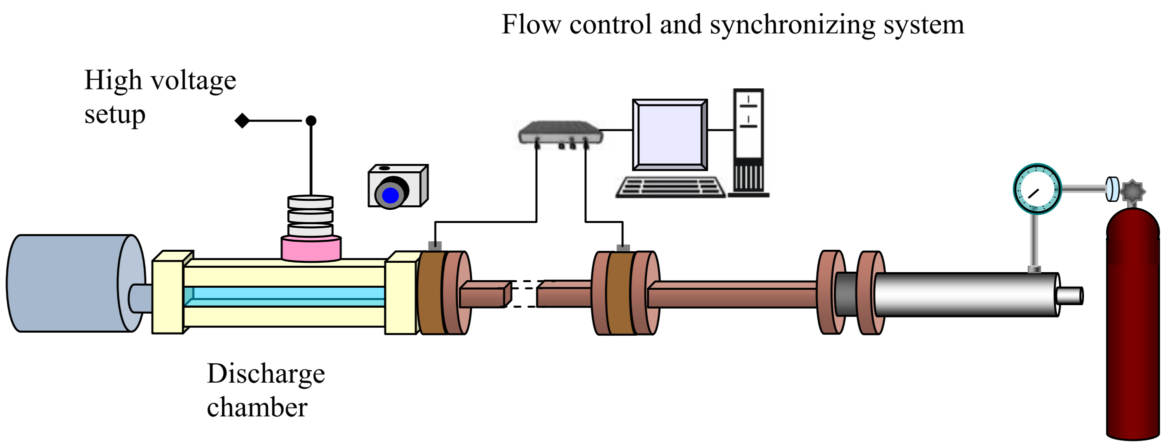


Figure 1. Experimental setup.

The special type of combined discharge – pulse volume discharge with pre-ionization by ultra-violet radiation from plasma sheets is used. The discharge is effective at creation non-equilibrium spatially homogenous plasma. The discharge is organized in two stages. At first stage (60-100 ns) the plasma sheets on the upper and lower surfaces of the discharge chamber burn. Plasma sheets are the system of channels sliding on a dielectric surface. They were initiated on two opposite walls of discharge chamber size of 30×100 mm an distance 24 mm from each other [2-4]. On the second stage pulse volume discharge was realized. Pulse volume discharge time was about 200 ns, the voltage was 30-40 kV, discharge current was about 1000 A. Due to ultra-violet gas pre-ionization by radiation from plasma sheets volume discharge is very homogeneous. Energy released into gas by volume discharge is transferred to electron-exited, vibration, rotation and then to translation molecular modes.

The definition of energy input's capacity on the "volume" stage was based on the measurement of discharge's voltage and current. In the concerned conditions averaged capacity of specific energy input equaled 0.03-0.06 eV/mol. The part of energy input in plasma sheets was about 12%. This part of energy input was concentrated in relatively thin layer [4].

The initiation of the pulse discharge in a supersonic flow in the rectangular shock tube channel allows ionizing supersonic gas flow in short time interval. In this time interval changes in configuration of flow discontinuities and non-homogeneities do not occur. So, the setup is used for experimental modeling of the process of instant creating of plasma area in supersonic flow with the different shock wave configurations. Piezometer's impulse from shock wave spreading in shock tube channel allowed to synchronize the initiating of discharge with the any stage of gas-dynamics non-stationary process. Integral glow of surface and volume discharges was registered by photo cameras through the windows of discharge section.

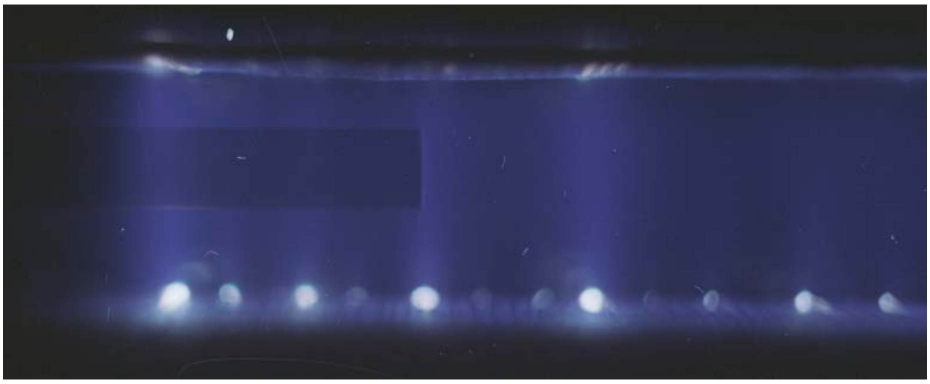
Researches of the discharge in the gas flow behind the plane shock wave after it's diffraction on some models were conducted. Different models were tested in supersonic and transonic flows; blunt cylinder (fig. 3), cone, cylinder (fig. 2), spiked cylinder, complex cone, cone with a hole. Models were mounted in shock tube – in discharge gap area with symmetry axes parallel to the flow.

The important feature of such experiments is presence of gas density's heterogeneous areas in pulse discharge zone. That leads to constitutive redistribution of discharge's current because of "strong" dependence of medium's local conductivity on the value of E/N (E is electric field, N is concentration). In this case discharge was self-concentrated in the low-density areas, which became the source of advanced intense of lighting.

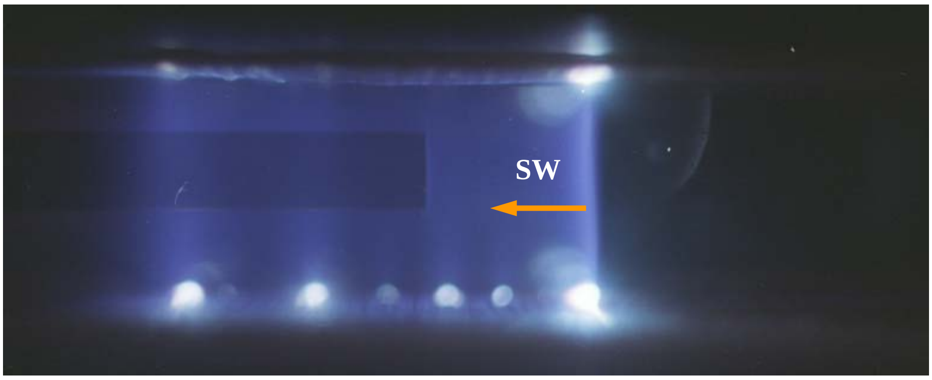
Experimental results

Experimental researches of plasma glow spatial map of nanosecond discharge in front of plane shock wave were made. Let's consider motion of a plane shock wave in a channel of a shock tube with constant speed. Parameters of gas behind shock wave are constant and they are defined by Rankine-Hugoniot relations. At some moment of shock wave passage through the working section of the channel there is a volume pulse ionization. Duration of flow ionization stage (time of a current through the discharge gap) is about 200 ns, i.e., as shown above, it is possible to consider energy input as instant.

Being homogeneous in homogeneous gas (Fig.2 a), the discharge is redistributed in a non-uniform gas flow according to its structure. Integrated recording of the discharge electroluminescence in a flow represents the image with an exposition of the discharge flash (~200 nanoseconds). Integrated recording of nanosecond discharge image in non-stationary gas flow in an expecting mode was used for analyzing of discharge redistribution in flow. Fig. 2 b is luminescence image of the discharge gap crossed by a shock wave (M = 2.3) which had passed about 50 % of electrodes' length. There is the cylinder with flat nose in discharge chamber mounted for the shock wave diffraction process investigation. The arrow indicates the shock wave movement direction. The discharges burn only in a zone of the low gas' density in front of a shock wave. Thus, at initiation of the discharge in the channel with a shock wave, gas-plasma plane border is created instantly (during 200 nanoseconds) on shock wave front. Gas flow ionization by the volume impulse discharge leads to volume discharge's current redistribution into the area of the low density. It occurs due to local medium conductivity dependence on the value of E/N. The discharge "localizes itself" into the low density area which becomes a source of the high intensity of a luminescence. At the moment of instant discharge energy release in front of moving shock pressure in discharge zone raised quickly - Rankine-Hugoniot relations on shock surface were violated.



a)



b)

Figure 2. Discharge image:
a) – in ambient air in discharge chamber;
b) – with plane shock in discharge chamber.

The maximal specific energy input value in these areas can be estimated as:

$$e = e_0 V_0 / V \qquad (1)$$

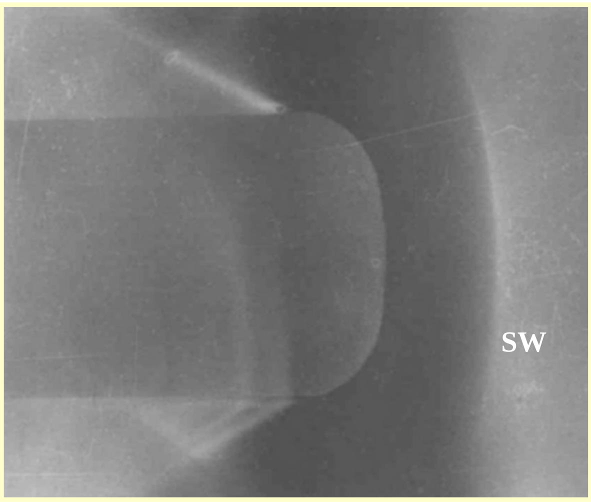


Figure 3. Discharge image with bow shock configuration.

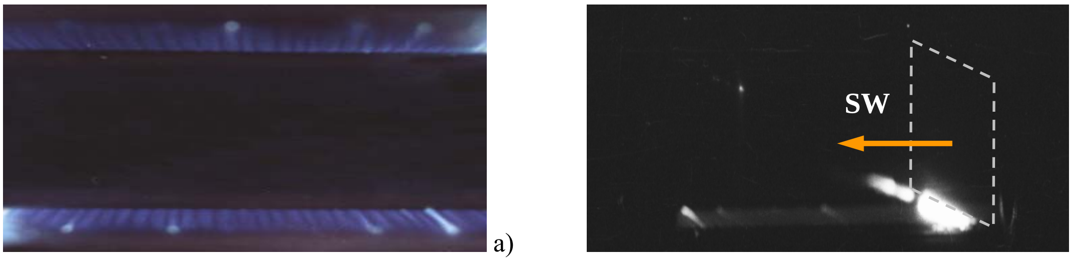
Where e_0 – energy input value in a homogeneous gap, V/V_0 – a fraction of ionization area in the discharge gap volume V_0 (100×24×48 mm). At some small values V this relation loses sense; the current of the discharge is redistributed in the discharge chamber.
Thus in presence of shock wave the discharge is redistributed in a non-uniform gas flow according to its structure. Integrated recording of the discharge luminescence in a flow represents the image with an

exposition of the discharge flash. Images of the discharge glow reveal that plasma is not absolutely homogenous along shock movement direction in the area between shock wave and discharge gap perimeter. Experiments revealed that discharge plasma glow intensity increases near front of shock (Fig. 2 b).

Pulse volume discharge was switched in supersonic quasy-stationary flow over blunt cylinder d=9mm mounted in shock tube. Bow shock wave in supersonic flow was investigated. Fig. 3 is the photo of discharge area with bow shock wave (M=1.5) around blunt cylinder. Shock layer is dark area of high density in front of model. Glow intensity in gas flow in front of bow shock wave increases towards the shock.

Fig. 4 a illustrates surface discharge glow on test camera walls in ambient air. Fig. 4 b is the photo of surface discharge's area with plane shock wave (M=2.3). The discharge (surface as well as volume) burn only in a zone of the low gas' density before a shock wave. The dotted line indicates the plane shock wave front position and the arrow indicates the shock wave movement direction. Also one can see that glow is not homogeneous. It is more intensive towards the shock surface.

Two types of discharges in supersonic gas flows were used for investigating of shock waves M=1,5-4,5 area ionization. It was shown that glow intensity in front of shock wave at pressure P=10-250 Torr increases towards the shock wave fronts at 200 nanosecond volume and surface ionization. Stationary discharge glow intensity redistribution near shock front is connected with discharge current across the shock front [5] The analysis of the mechanism of the glow redistribution effect in nanosecond discharge requires further researches.



a) b)

Figure 4. Surface discharge image: a) – in ambient air in discharge chamber;
b) – with plane shock in discharge chamber.

Acknowledgements

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