DOI: 10.13009/EUCASS2017-670

High speed flow control with nanosecond discharge.

Znamenskaya Irina, Ivanov Igor*,**, Mursenkova Irina*, Naumov Dmitry**
**Lomonosov Moscow State University*
MSU, Faculty of Physics, Russia, 119991, Moscow, GSP-1, 1-2 Leninskiye Gory
***Moscow Aviation Institute*
125993, Moscow, Volokolamskoe shosse, 4

Abstract

The paper deals with the problem of pulse discharge localization in a supersonic and transonic non-homogeneous flow and its use for flow control. Discharge plasma was shown to be localized in zones of low density – in front of shock wave and in vortex separation zones – at rear side of the wedge and at shock interaction with boundary layer. The amplitude of electric current localized in vortex may be twice higher than in homogeneous gas flow.The Riemann problem conditions on ionized shock wave front are confirmed by series of images, obtained with high speed shadowgraphy.

1. Introduction

The paper deals with the problem of gas flow control by using pulse discharge localization in a supersonic and transonic flow. A number of the publications was devoted to plasma flow control in recent years. During the last few decades, the effect of energy deposition on the structure and dynamics of high-speed flows and shock waves has been intensively investigated, both experimentally and numerically, primarily motivated by applications of active flow control in aerodynamics. The methods of energy deposition to the flow, which are usually considered, involve different types of gas discharges (plasma actuators [1]), laser pulses, electron beams. The gas breakdown results in the formation of a non-equilibrium plasma, with properties depending on the discharge type. The plasma-based devices have been proposed and studied as a means for wave drag reduction, boundary layer separation, sonic boom mitigation, shock waves modification, high-speed jet control.
Depending on the ratio of the energy deposition time, td, to the fluid dynamical time scale, tgas, two energy deposition modes can be obtained: stationary ($t_{dis}//t_{gas}>=1$) or pulsed ($t_{dis}//t_{gas} <<1$) energy deposition.
The pulsed (or pulsed-periodic) mode is, preferable in some practical applications in terms of energy efficiency. Pulsed surface discharges are capable of heating a thin layer of gas near the dielectric surface, on a sub-microsecond scale, and generating a shock wave, providing a mechanical impulse to a surrounding gas [1-4].
If the high speed flow has some structures (shock waves, vortexes, rarefaction waves), the inhomogeneity of the gas flow density leads to a significant inhomogeneity of the gas conductivity. It may result in the quick discharge current redistribution. Parameter E/N sharply drops on the shock front where E is the electric field strength and N is the concentration of neutral particles in the discharge plasma. The result of quick local plasma energy input is the shock (blast) waves initiating, moving from localized plasma configuration.
In this paper, we describe the results of investigations of a nanosecond transversal spatial discharge with plasma electrodes experimentally realized in supersonic flow at the wedge in the channel. Discharge can be used for rapid heating of the gas flow area behind the wedge and flow control based on quick heating and shock waves production.

2. Experimental setup

An experimental setup was shock tube mounted with a specially constructed discharge chamber. Setup was built for the purposes of studying the non-stationary processes of interaction between the subsonic or supersonic gas flows and spatial or surface short-termed electric discharge [4]. In considered conditions the words “short-termed” mean that discharge electric current duration, which is about 200 ns, is much less than characteristic time of gasodynamic processes realized in the shock tube. So, the impact of the discharge could be considered as instant energy input from the gasodynamical point of view. The shock tube had a channel with the rectangular profile of 2.4 x_4.8 cm^2. The

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discharge chamber was mounted with the shock tube's channel and it had the same rectangular profile. Shock waves with Mach numbers M=1–4.5, were tested, using helium as a driver gas and the air as a driven one. The top and bottom walls of the chamber were the plasma electrodes which produced the ultraviolet glow for the preionization of the spatial discharge area. Such configuration of the discharge section allowed improving the homogeneity of the spatial discharge. The initiation electric impulse leads first to the development of sliding surface discharges of two plasma electrodes. Their ultraviolet glow produces a pre-ionization of spatial area. After ~ 30 ns the spatial discharge's current starts. After that spatial and sliding discharges glow simultaneously during ~ 150—200 ns. Sliding surface discharge (plasma electrode) has a structure of parallel discharge channels on a dielectric surface.Synchronization system allowed to switch the nanosecond-lasting discharge in different moments of shock-wedge interaction and in stationary flow. The discharge glow is quite homogeneous all over the discharge section in quiescent air. The chamber's sidewalls were made of quartz glass for flow visualization, (shadow and schlieren technique; glow images in discharge chamber).

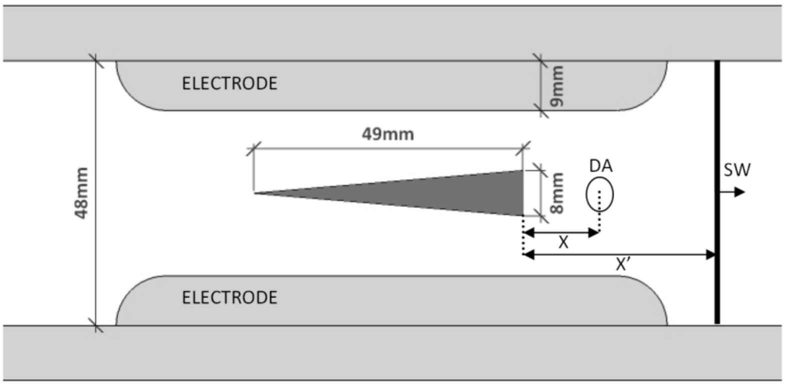

Figure 1. Wedge in the test camera.

If the discharge was initiated at the moment when shock wave front situated in the discharge section, the discharge energy and glow concentrates in the low pressure area in front of shock wave. This phenomenon of discharge "self-localization" in low density area was observed for different flow configurations. Accumulation the discharge glow in the low pressure area is caused by the fact that the local conductivity of the air is the a sensitive function of parameter E/N. Areas of low pressure, great value of E/N (in front of shock wave or in vortex) are areas of big local conductivity and discharge energy is localized there. It was shown [5, 6] that about 20%–50% of the high current nanosecond discharge's energy may be directly converted to the gas heating of gas in front of shock wave. The vibrational-translational relaxation time for the other part of the discharge's energy is more than 10^{-4} s, so under the conditions of the described experimental setup, we may consider only the instant part of the energy release.
The wedge of 10° angle was mounted in the discharge camera of shock tube (Figure 1). When shock wave was interacting with a wedge, passing through the discharge section, discharge was switched on. Plasma glow redistribution in non-stationary inhomogeneous flow was recorded at 3 angles of view through camera windows.

Experimental results.

If the shock wave is passing along the wedge, the glow concentrates in the low pressure area in front of the shock wave or in some zones of density gradients. When shock wave had diffracted over the wedge, the vortex separation zone is formed at the rear wall of the wedge. So area of low density and high conductivity behind the wedge becomes the zone of discharge plasma localization and energy concentration. The phenomenon of discharge "self-localization" was observed for different stages of process in shock tube using integral glow recording,
Figure 2 presents integral image of flow ionized with pulse volume discharge on different stages of shock wave

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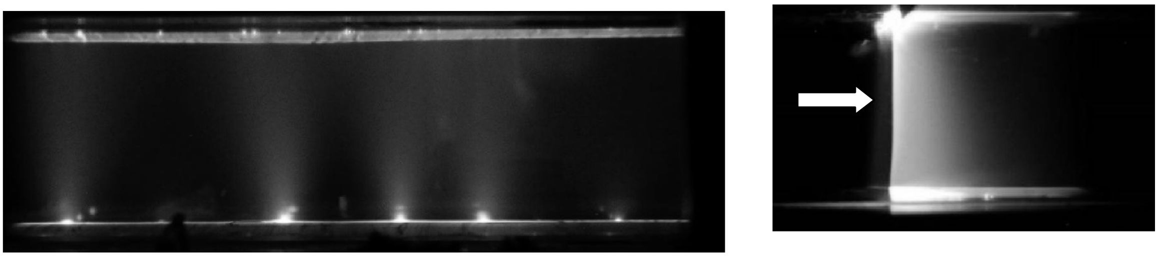
movement through discharge camera channel. These are instant images of glow in quiescent air (2a) and plasma redistribution (2b) in inhomogeneous flow. Phenomenon of discharge self-localizati in front of shock is recorded on Fig. 2b. Plane shock wave is moving from left to right. Glow (of sub-microsecond duration) is in front of it on instant flow image.



a b
Figure 2: volume discharge in quiescent air and in front of shock wave.

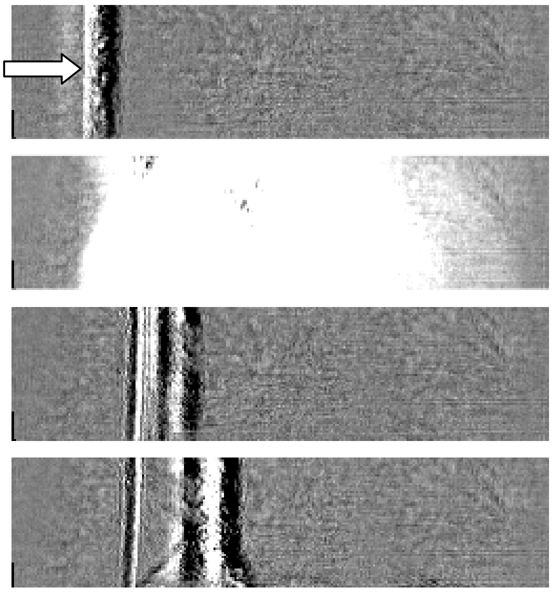


Figure 3. Gas flow after the discharge: Riemann problem.

The discontinuity breakdown (effect of Riemann problem) on shock wave front interacting with plane surface of nanosecond discharge localized by the shock surface is confirmed by shadow images, obtained with high speed camera Photron Fastcam SA5 (Fig.3). Initial shock wave moving from left to right is impacted by volume localized discharge; as a result we have 3 discontinuities (Riemann problem): shock wave moving to the left, shock wave moving to the right, contact surface between them.

Fig. 4 presents the effect of discharge glow instant redistribution when discharge is switched on after shock diffraction on the wedge. Flow velocity is from right to left. Fig. 4a: wedge nose area: discharge was switched 200 µs after shock wave has passed the tip of wedge. Fig.4 b: rear side of wedge; discharge plasma is localized into vortex zone which had formed behind the wedge after shock had passed. The discharge was switched 70 µs after shock wave has passed the wedge end. The flow sketch is below: black points are the separation zones – areas of pulse discharge localization.

3. CFD simulation

A two-dimensional 2D numerical simulation under experimental conditions were conducted. We use a framework of time-dependent 2D Euler equations model for numerical simulations. It helped to analyze the flow parameters before and after that instant energy release into separation zones. A comparison of numerical data and shadow images of a

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2D flow after shock wave interaction with the discharge area was conducted. Adequacy of the used model is supported by experimental shadow images of the flow area after energy input in front of plane shock wave [5].

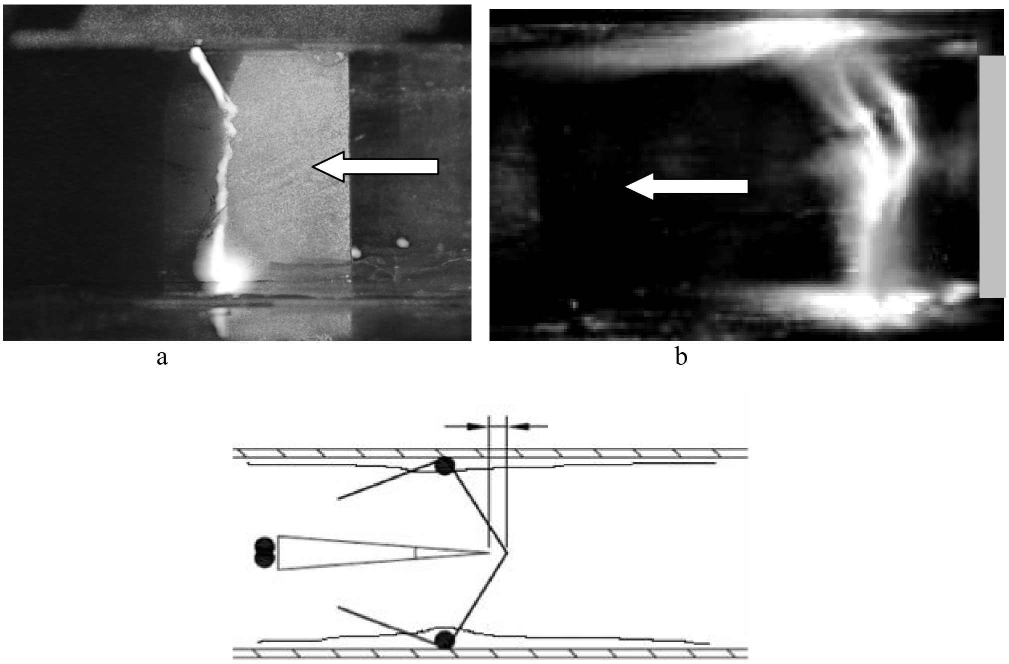

Figure 4. Discharge configuration at different moments of shock diffraction on wedge.

The computational domain has taken assuming the symmetry plane of the flow existence. The discharge is modeled by an instantaneous energy input in the zone in area of energy localization. The energy input with constant density E=3 10^5 J/m^3 is considered. The energy input increases specific internal energy for a given amount. The gas medium is air γ =1,4. The mathematical model of the Euler equations for two-dimensional unsteady flows in Cartesian coordinates was used. The initial parameters correspond to the undisturbed flow at a fixed gas pressure of 75 Torr. The system of Euler equations was solved using finite volume MUSL type scheme with spatial reconstruction of the fifth order and the third-order Runge-Kutta approximation on time. The flows through the cell faces were calculated using the approximate AUSM method for the Riemann problem. CFD computations were performed at various grid point numbers. Accuracy of numerical scheme up to fifth order has been demonstrated. In comparing CFD and glow and shadow images, the plasma localization and gas dynamic configurations of the shock wave – pulse discharge interactions were understood.

CFD density flowfield and discharge glow at the subsequent moment are on Fig. 5. Flow is from right to left. Plasma glow redistributed into double low density areas: in front of passing diffracted shock wave (1) and behind the wedge rear side in the vortex separating zone (2). Mach number is 3.3, discharge time is 20 µs after shock wave has passed the wedge end.

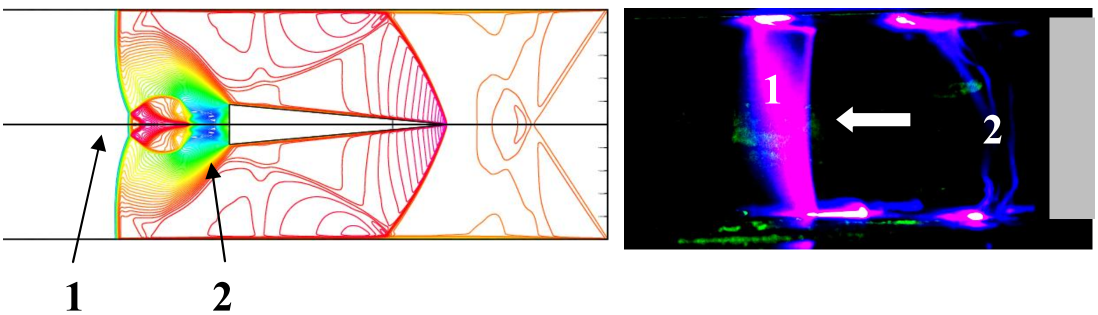

Figure 5. CFD simulation of flow density and experimental instant image of discharge glow at the subsequent moment.

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1D and 2D CFD simulation of Riemann problem was also conducted for different values of discharge energy. Shadow images of discontinuities dynamics (see Figure 3) were compared to CFD simulations. It was shown that energy localization into gas, leading to discontinuities arising and evolution recorded in experiments is about 50% of discharge capacitor energy and is up to 0,5 eV/particle in localized discharge area.

4. Conclusion.

Initially homogeneous volume discharge was switched in non-uniform high speed flow. CFD analysis of flow density fields in non-uniform non-stationary 2D gas flow was carried out. Pulse discharge plasma was shown to be localized in zones of low density – in front of shock wave; in vortex separation zone – at rear side of the wedge and as well at zone of shock interaction with boundary layer. Energy of the localized electric discharge current was converted instantly (in 200-500 ns time) to shock waves, gas heating, molecules rotation, vibration, ionization, and electrons excitation. It was shown that redistribution of energy input leads to energy localization up to 0,5 eV/particle in plasma localization area. High speed flow control may be based on nanosecond discharge localization, leading to shock waves action on flow.

Acknowledgments

This study was supported by the RFBR Grant № 17-08-00560

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