SUPERSONIC/TRANSONIC FLOW CONTROL BY ELECTRO-DISCHARGE PLASMA TECHNIQUE

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Keywords: *Flow Control, Non-Equilibrium Plasma, Separation*

Abstract

The paper is devoted to the problem of high-speed dense flow management by plasma of electrical discharges excited inflow. The results of wind tunnel experiments with the DBD and quasi-DC discharges generation near streamlined surfaces in high-speed airflow, analytical and CFD efforts are presented. The idea of significant role of non-equilibrium gas excitation is under development. The control of structure of supersonic duct-driven flow is demonstrated experimentally.

1 Introduction

It is apparently now that plasma methods based on electrical discharges generation have a practical potential for a high-speed flow control. An idea of the method can be formulated on the most simple manner as following: modification of flow-field structure and, consequently, changing a pressure and tangential tension near surfaces by means bulk forces excitation in EM fields and heat release into predefined location with predefined parameters' distribution and at predefined tempering.

Recently the potential of modification of supersonic/transonic flow characteristics in free stream, in ducts and near surfaces using electric discharge plasma has been discussed widely [1-10]. Several ideas stimulate efforts in this field: drag reduction, control of the inlet/diffuser performance, the improvement of the supersonic combustion efficiency, surface discharge effect on viscous friction, etc.

This paper considers two situations with surface discharge in high-speed flow: transonic flow around profiled airfoil with DBD actuation of boundary layer [9], and consequence of transversal quasi-DC discharge generation near plane wall in supersonic flow [7]. In both cases plasma effect can't be reduced to trivial heating of the gas.

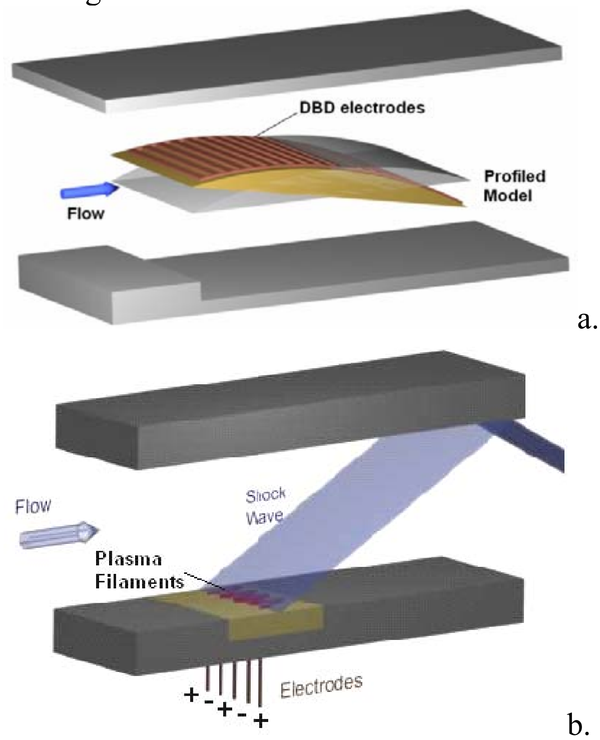

Fig.1. Experimental arrangement: transonic test of DBD equipped profiled model (a), and supersonic test of transversal DC discharge on the wall (b).

The non-thermal mechanisms of the plasma effects are appeared by two ways mostly: nonequilibrium excitation and volumetric forces generation in electromagnetic fields (electrostatic due to charge separation and magnetic due to Ampere's force). If the nonequilibrium excitation of the gas takes place the area of power deposition doesn't equal with the area of temperature increase. Such a discrepancy is important when a typical gasdynamic time $t_{gd}=X/V$ is compatible or less with a relaxation time. By the other words the length of relaxation may be compatible with a size of streamlined object. A few types of excitation can be listed, but in the dense air the vibrational excitation of nitrogen seems to be the most important.

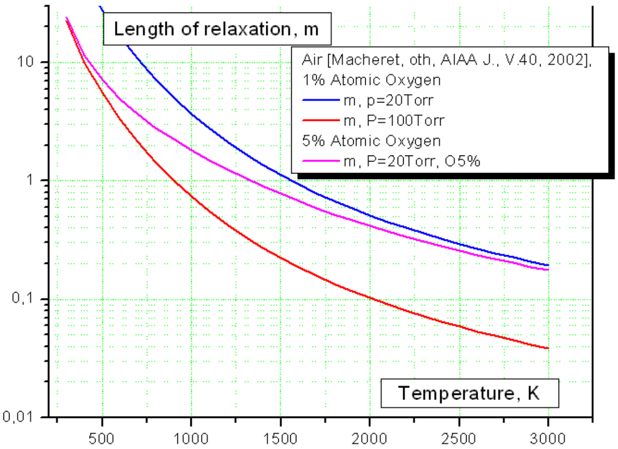

Fig.2. Estimation of V-T relaxation length at flow velocity V=500m/s

The Fig.2 gives an estimation of vibrational-translational relaxation length at flow velocity M=2 in dependence on temperature. It is calculated on the base of [11]'s data. Well seen that in high-speed flow such a length can have meters of amplitude. Among others two practical effects are under expectation. As a rule the effect of heat release, associated with plasma generation, impedes a result of MHD or EHD interaction. If the plasma is nonequilibrium, temperature is enough low, and velocity is high, the area of heat deposition occurs downstream of interaction zone. The second consequence concerns a shape of extrusive layer downstream of the plasma location: the expansion can be realized due to VT relaxation instead of narrowing due to cooling.

It is easily to estimate that Electro-Hydro-Dynamic/Electrostatic (EHD) effects might be significant under low-speed conditions or in distances compared with Debay's radius. But under the conditions of boundary layer and strong non-homogeneity of medium the mechanisms of charge separation and thermal electromotive force generation should be taking into account. A resonant effect could also multiply the result [7, 10]. Vise verse to that the magnetic forces on current in the gas can be quite valuable. The velocity of discharge-induced flow exceeds sonic level at electric current $I_{pl}=10^2\text{-}10^3A$ in magnetic field $B=1Tl$. Additionally in transversal external magnetic field the reduced electrical field in cannel of DC electrical discharge can be increased that is favorable for non-equilibrium effects appearance. Recently the appropriate aerodynamic phenomena were demonstrated experimentally [10, 20-21].

2 Experimental Facility PWT-50

The experiments were conducted in a short-duration blowdown wind tunnel PWT-50 with a closed test section Y×Z=72×60mm at Mach number M=0.85-2.0 and static pressure P_{st}=100-500Torr. The experimental facility is equipped with a Schlieren system, high-speed video camera, fast line-scan camera, IR camera, set of fast-response pressure transducers, spectroscopic system, photo-sensors, current-voltage sensors, thermocouples and a set of control-measurement devices. Two aerodynamic configurations are under analysis: profiled plate with surface dielectric barrier discharge (DBD) in transonic flow M_0=0.85-0.95 (Fig.1a), and transversal surface discharge on wall of the duct in supersonic flow M_0=2 (Fig.1b).

3 DBD Effect on Flow Structure over Profiled Plate in Transonic Flow

Last time numerous papers concern the boundary layer (BL) actuation by glow, corona and dielectric barrier discharge (DBD) [12-18]. These discharges directly act on gas momentum through the mechanism of charge separation. At the same time plasma-induced velocity is rather small for high-speed flow control. Another mechanism of separation control by DBD is increasing the flow stability (separation prevention) through BL turbulization. Each situation should be considered individually to define the exact mechanism of interaction.

The structure of surface dielectric barrier discharge (DBD) strongly depends on parameters of power supply. Roughly speaking, two modes can be considered: long filaments (they look like streamers) and multi-coronas. The first structure is realized at essentially high rate of the voltage increase ($dU/dt>10^{11}$V/s) and appropriate electrodes arrangement. The second mode can be observed at relatively moderate value of reduced electric field. Discharge is non-uniform in micro-scale in both cases [6, 18]. The multi-coronas mode is more effective for gas momentum generation: V_{ind}=1-8m/s at power W=0.5-10W/cm^2.

A profiled plate with non-symmetric electrodes configuration was utilized in the test, see Fig.1a for arrangement. The supplying power has following parameters: bipolar pulses of triangle shape with frequency 100kHz and amplitude up to 5kV. The upper electrodes have width Δx=1mm and insulator thickness 0.5mm. Base electrodes were shifted on 1mm in respect of upper ones. The velocity of the plasma-induced flow was measured by means of analysis of Schlieren streak video images and by direct pressure measurements. A sample of velocity distribution is shown in Fig.3 for the typical conditions and atmospheric pressure. It is well seen that the multi-corona discharge gives a gas jet with a length about 10mm just near the surface. Downstream and above this place the gas moves typically as for a mixing area. It is clear that in high-speed co-flow this layer will be thinner.

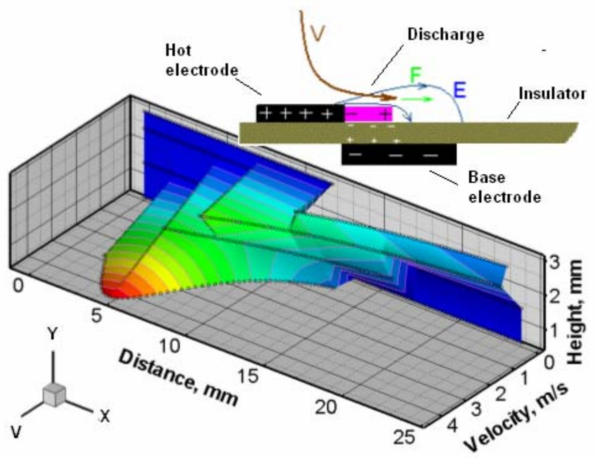

Fig.3. Scheme of DBD excitation and experimental data on plasma-induced flow.

It is important to estimate a maximal effect of electrical field on flow, and an influence of individual parameters on the value of induced velocity. The estimation is fulfilled in frames of mechanism of electrical charge separation in electrical field at the gas ionization in discharge. A rough scheme is shown on insertion in Fig.3. A maximal electrical charge, which is accelerated by the electrostatic force $F_E=eE\times(n_i^+-n_i^--n_e)$ can be estimated through the electrical current: $q=I_{pl}\times\tau$, where τ - is the pulse duration defined by the charge deposition on the dielectric surface (the value of τ can be estimated through ions drift or measured experimentally). The mechanical impulse of this charge in electric field transfers to movement of a gas portion near the surface $V(\rho V\times\delta\times z^*)=E\times I\times\tau^2\times f$, where ρ- gas density, δ- accelerated layer thickness, z^* – effective depth of electrode occupied by plasma, f-frequency of oscillations. A simple transformation gives:

$$V_{ind}=\tau\times\sqrt{(\frac{E}{n}\times\frac{I}{\delta\times z^*}\times\frac{N_a}{\mu}\times f)},\ \text{and}\ \tau\approx\frac{\delta}{bE},$$

where b – drift mobility of ions. For the conditions of the experiment this equation gives value $V_{max}\approx 10m/s$ that is not far from experimental one. Taking into account real physical limitations, we don't see a way for significant increasing of this value. For example, an increasing the discharge current density leads to intensive heating of the dielectric surface due to active particles deposition but not a rise of induced velocity.

The electrostatic force is small compared to the total momentum in flow at high speed but, probably, it can transfer the momentum of the main flow to the boundary layer. The next idea is that such an induced velocity is compared with a level of turbulent modulation, i.e. it can be an effective method for artificial turbulization of boundary layer at high-speed.

The parameters of plasma-induced flow at external co-flow were modeled numerically. It is considered airflow over a surface with a dielectric barrier discharge (DBD) that is generated on a set of thin and narrow electrodes placed on the streamlined surface perpendicular to the velocity vector of incident flow. It is supposed that the electrodes of opposite polarity are placed inside a streamlined body with a downstream shift with respect to external electrodes. In this case the DBD is generated from downstream edges of external electrodes.

Numerical simulation of the DBD influence on a boundary layer is carried out exclusively in frames of equations of unsteady compressible laminar boundary layer with additional terms in momentum and energy equations, which simulate a force and heat impact of the DBD. It means that an electrodynamic describing of the physical phenomena in the discharge is not considered. However an influence of non-equilibrium degrees of freedom in total energy transfer is taken into account.

The free stream parameters have been defined the same as in experiment (see below): the total temperature is $T_0=290K$, the Mach number is $M_\infty=0.95$, the static pressure is $p_\infty=8\times10^4 Pa$, the plate length is $l^*=0.1м$ (characteristic length scale), the Reynolds number is $\mathrm{Re}=2.2\times10^6$. The non-dimensional time of the vibrational energy relaxation is defined as $\tau_{VT} = u_\infty^* \tau_{VT}^* / l^* \cong 60$. The single pulse energy $E_{imp}=10^{-3} J/m$ and the maximum values of the volume force components remained invariable too: $F_{x0}^* \cong \varepsilon_0^* E_0^{*2} / h_x^* \cong 2{,}2 \cdot 10^5 \, N/m^3$; $F_{y0}^* \cong -2\varepsilon_0^* E_0^{*2} / h_y^* \cong -2{,}2 \cdot 10^6 \, N/m^3$. E_0^* is electric field strength, upper stars in symbols mean dimensional values.

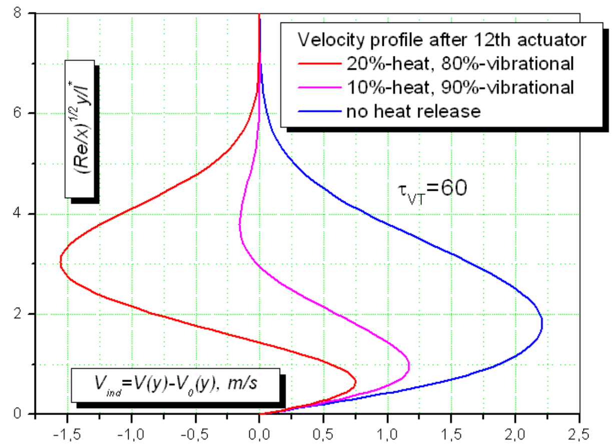

Fig.4. The plasma-induced flow velocity profile in transonic co-flow at heat release switched on/off.

The Fig.4 demonstrates profiles of averaged induced velocity in middle section of the model. A thermal effect was switched off and on correspondingly. The result is obvious: a thermal influence of the DBD on boundary layer at a deficient volume force momentum can prevail over its force action resulting in an appearance of negative induced velocity as a consequence of gas heating and boundary layer thickening.

As it was mentioned above the corona and barrier types of electrical discharges effect on flow parameters at low flow velocity V=3-50m/s. It appears in separation prevention at high angles of attack and in some reduction of turbulent friction. At larger velocity of external flow the effect was negligible. In some cases the mechanism of interaction is announced as electrostatic but in the most works it looks as thermal turbulization of boundary layer by DBD pulsing. Vise verse to such an approach a thermal influence of DBD can be eliminated in high-speed flow due to blowing out of V-excited gas. But to observe a weak electrostatic effect at high velocity a sensitive aerodynamic situation has to be chosen. The experiment was fulfilled on the observation of transonic shock position over profiled model with surface-mounted DBD generator. To increase the DBD electrostatic effect the frequency of DBD oscillations was adjusted on resonant manner: Strouhal number was $St=1$ in respect of inter-electrodes distance.

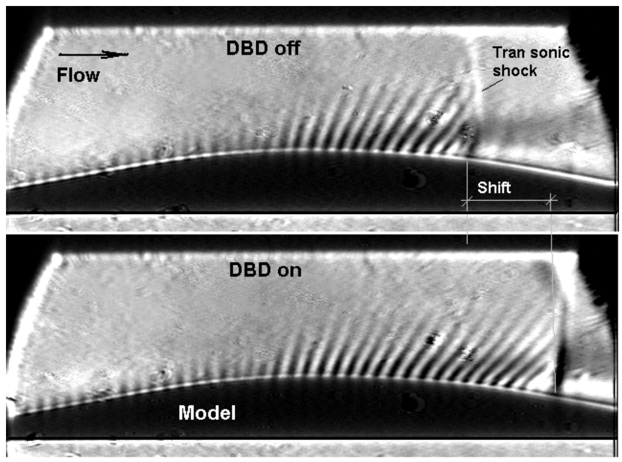

Fig.5. Schlieren photos of the DBD effect on boundary layer under transonic flow.

A comparison of two Schlieren photos (DBD off - DBD on) of such a mode is shown in the Fig.5. It is well seen that transition zone between supersonic mode of the airflow and subsonic one is shifted downstream when the discharge is switched on (second photo). Generally two main mechanisms may guide a shift of transonic shock over profiled airfoil: thermal and electrostatic (non-thermal). In the first case the shock has to be shifted upstream [19]. In the second case the effect may have both directions in dependence on the electrostatic force vector (direction of the plasma-induced flow). The fact that it is shifted downstream, when the additional force directed on the same manner, prove the conclusion on electrostatic mechanism of interaction.

4 Surface transversal DC discharge effect on flow structure

Two the most intensive mechanisms of plasma-flow interaction are the gas heating and Ampere's force in external magnetic field (MF). The first mechanism acts through pressure redistribution, the second – by direct addition of momentum to gas portion with electrical current. Here an attention is arrowed on two important effects of near-surface plasma excitation: extrusive layer parameters and artificial plasma-induced separation.

4.1 Extrusive layer thickness

An extrusive layer is located downstream zone of electrical discharge generation due to gas heating and following expansion. The X-profile of it is critically important for analysis of consequences in terms of flow structure modification. One of examples is related to plasma gearing of inlet's configuration, when oblique shocks are applied for regulations of initial flow compression. Local condensed heat release leads to local flow modification as well. The idea of extrusive layer lengthening due to deferred VT relaxation is quite promising to solve the problem.

Consider a planar inviscous flow along a plane with surface electrical discharge burning perpendicular to the flow direction. Denote the discharge region width in the flow direction - l_d, and discharge thickness above the plane surface - h_d. Specific discharge power $W = jE$ is distributed by electrons between vibrational and electronical excitation of molecules and straight gas heating; the corresponding parts of discharge power are denoted η_v, η^*, and $(1-\eta_v-\eta^*)$, respectively. The energy stored in vibrationally and electronically excited states of molecules transfers into heat during τ_{VT} and τ^* time, respectively.

If the discharge region length l_d in the flow direction is shorter than vibrational-translational relaxation length $l_{VT} = u_1 \tau^*_{VT}$, then the delayed energy extraction into the flow due to vibrational-translational relaxation has been shown to form an extrusion layer of thickness h near the surface [9,20]:

$$y(x) = h_d \exp\left[\alpha_W \left(1 - \exp\left(-\frac{x}{l_{VT}}\right)\right)\right],$$

where $\alpha_W = \dfrac{(\gamma-1)\eta_V l_d W}{u_1 a_1^2 \rho_1}$ - is the relative vibrational energy stored in the flow due to discharge; l - the distance from discharge location; u_1, a_1, ρ_1 are velocity, speed of sound and density of oncoming flow, γ - specific heat ratio. Relative layer thickness y/h_d versus relative distance x/l_{VT} is shown in Fig.6 for different α_W values.

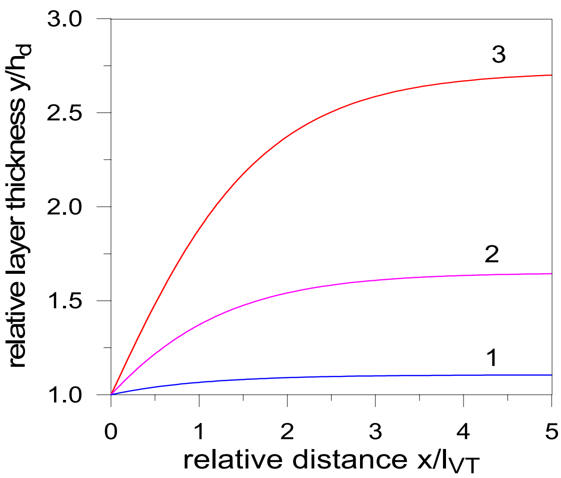

Fig.6. Relative layer thickness y/h_d versus relative distance x/l_{VT} for $\alpha_w = 0.1$ (1), 0.5 (2) and 1.0 (3).

To obtain notable expansion of extrusion layer the discharge power should be high enough to satisfy the condition $\alpha_W > 1$ or $W > \dfrac{M_1 a_1^3 \rho_1}{(\gamma-1)\eta_V l_d}$. For 30 km altitude flight conditions ($p \approx 10$Torr, $\rho_1 \approx 1.8\times10^{-2}$kg/m^3, $T_1 \approx$

230K,) the factor $M_1 a_1^3 \rho_1 \approx 40 M_1$W/cm^2, and $\alpha_W > 1$ for discharges with $W > 10^4$ W/cm^3, $\eta_v \approx$ 0.7-1, and $\tau_{VT} >> h_d/a$ (see Fig.2). Such W values are achievable in arc discharges, and $\eta_v \approx$ 1 is typical for glow and low temperature arc discharges in air.

4.2 Discharge in flow and MF

Plasma cord dynamics in the flow with and without external MF was explored using high-speed CCD camera and line-scan camera. Permanent magnetic field with amplitude up to B = 1.2 T is directed perpendicular to the surface. The electrical current direction can be changed for desired direction of magnetic force. Line-scan camera is adjusted on axial line between electrodes along the flow. Stagnation/static pressure distribution and volt-ampere characteristics were also measured.

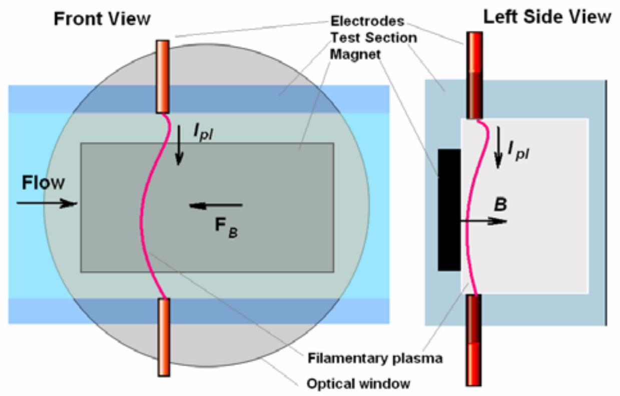

Fig.7. Experimental scheme of plasma dynamics study in flow and external MF.

The scheme of the model experiment in high-speed flow is shown in Fig.7. Static pressure was P_{st}=720-100Torr at initial Mach number M=0.2-2. Quasi-DC discharge was excited in transversal mode. The electrodes were flush-mounted on top and bottom walls of the duct just near the surface. The electric power input to plasma volume was W=3-10kW for inter-electrode distance 50mm. Typical electric current through an individual electrode I_d $\approx$ 5-50A, the duration of plasma pulse was τ=20-150ms. Translational temperature of the gas has been measured inside discharge cord using spectroscopic technique. The typical values were T_g = 3.5-6kK depending on experimental conditions. The input power increase leads to slow growing of maximal temperature. The vibrational temperature weakly depends on power input and in the case of moderate power deposition was higher than transitional one $T_v \approx$ 8-10kK.

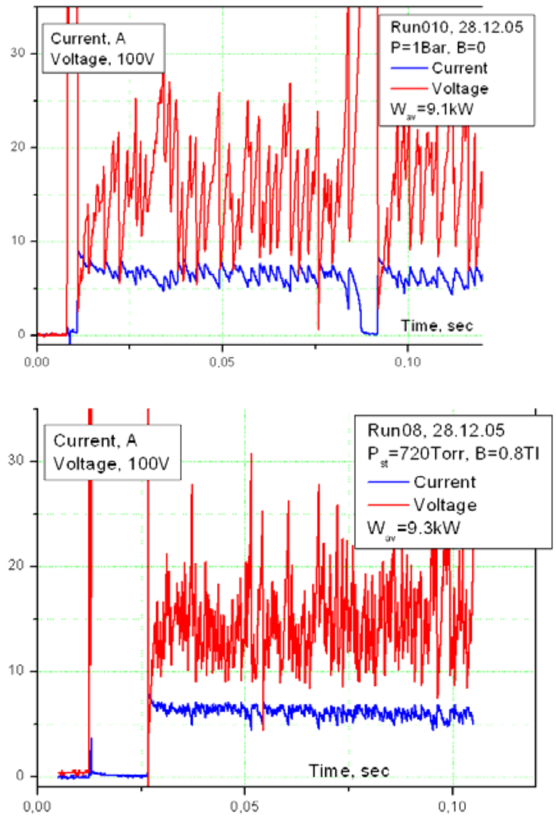

Fig.8. Volt-ampere record, M=0.2, Pst=720Torr, B=0. Relaxation mode (a); B=0.8Tl. Slowed mode (b).

If the discharge burns without MF a standard relaxation mode takes place: plasma cord is blown down by the flow with velocity $V_{pl} \approx 0.8\text{-}0.9V_0$. The frequency of relaxation depends on flow velocity and length of plasma loop (that is a function of power supply parameters). It was f=5-10kHz. Reduced electric field was E/N = 5-30Td depending on pressure, flow velocity and current.

If MF is applied for discharge generated inflow (the F_m is directed ahead), the plasma channel motion is slowed down up to complete stagnation or even reverse of speed. In the stop-mode the translational gas temperature drops due to intensive cooling by the flowing gas; the length of discharge filament is decrease; frequency of oscillations are grows; and the reduced electric field rises up to E/N = 50-70 Td in stop mode. Discharge plasma becomes more non-equilibrium with higher level of vibrational excitation. This mode is favorable for huge extrusion layer generation. Samples of voltage-current record are shown in Fig.8 without MF (variant "a") and in external MF (variant "b"). It should be noted that the deposited power is almost the same for these regimes.

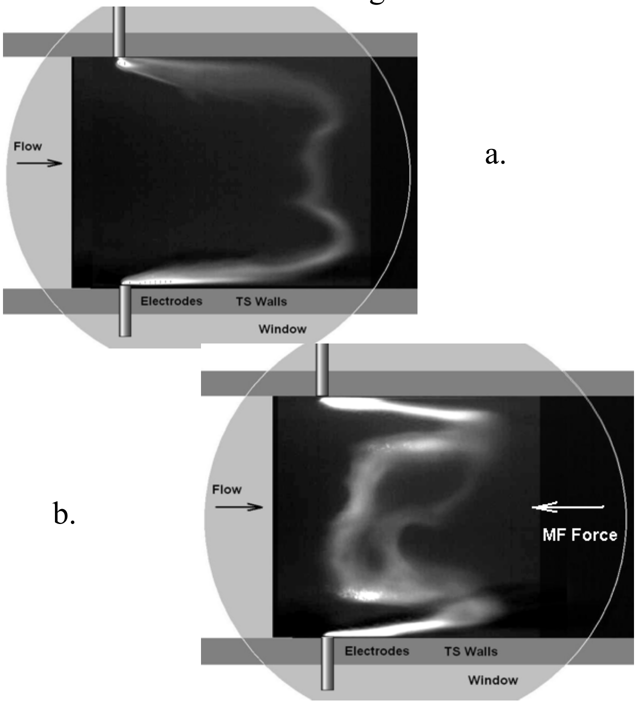

Fig.9. Plasma filament in flow, B=0 (a). B=0.8Tl (b).

Typical image of the discharge loops in two variants are shown in Fig.9a and 9b correspondingly. To make a stop-mode the values of main parameters have to be in definite relation. The induced transversal plasma filament's velocity V_{ind} should be equal to the flow speed. Actually such a mode is unstable if no irregularities of MF or flow structure are. But the Ampere's force $\boldsymbol{F_B}$ and gasdynamic forces $\boldsymbol{F_{GD}}$ can be equalized by current adjustment and the plasma filament affects on flow significantly. The conditions can be estimated roughly on the base of the following consideration.

$$F_B = [I_{pl}\times B]\times L, \qquad F_{GD}=c_d\times\rho/2\times V_{ind}^2 Ld,$$

$$F_B=F_{GD},\ V_{ind}=V_0 \ \Rightarrow\ \rho\times c_d\times d\times V_0^2\approx 2I_{pl}\times B,$$

where $\boldsymbol{d}$ and $\boldsymbol{c_d}$ are effective filament's diameter and effective drag factor of the plasma filament with attached mass. The diameter of plasma channel is a complex function of density, temperature, current, and velocity of external flow. Practically the sound velocity in ambient air can be achieved at B = 0.1-1 T and I_{pl} = 100-1000 A approximately.

The direct measurements of pressure redistribution shows that MF application amplifies the effect of flow braking due to discharge generation significantly without an increasing of the power deposition [21].

4.3 Flow Control in Inlet's Configuration

We pose the results of this section as a demonstration of non-equilibrium plasma advantages to control of supersonic flow structure. The experimental scheme is shown in Fig.10 as well as the scheme of modeled 3-SW inlet. Oncoming flow in duct with height Y_0=*50mm* has Mach number M = 2 and static air pressure P_{st} = 100-300 Torr. The measured translational gas temperature in discharge zone is about T_g=*3000K*, so, the length of relaxation could be expected in value of several centimeters (see Fig.2). All electrodes were flush-mounted and don't affect the flow themselves. To recognize the effects of VT relaxation the experiments were fulfilled in air, argon (no VT excitation) and carbon dioxide (short time of VT relaxation).

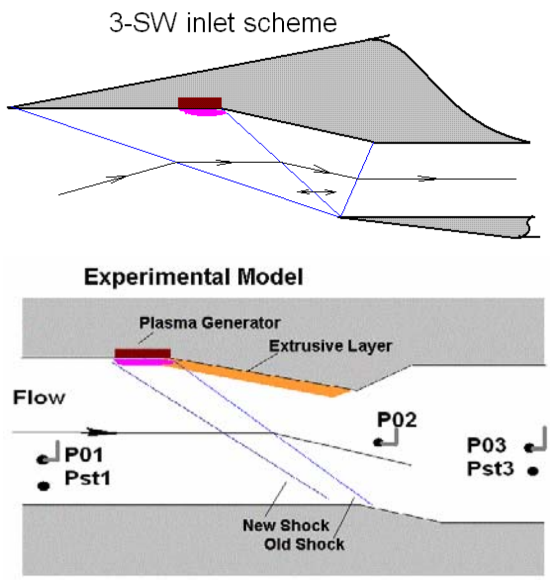

Fig.10. Experimental scheme of quasi-DC discharge tests

The Figs.11a,b and 12 present the typical data of the model configuration test in air. The first photo is the Schlieren image of undisturbed flow structure. The second photo shows the flow structure when the plasma generator was switched on. The insertion allows recognizing the thickness of the extrusive layer on the wedge downstream the plasma area (post-plasma layer). The Fig.12 presents data on pressure distribution measurements: P01 is a stagnation pressure upstream (in fore-chamber); P02 is a pressure from Pitot pipe at a distance 100 mm downstream of the plasma zone; P03 is measured at the end of the duct (200 mm downstream); Pst1 is a static pressure upstream of the interaction zone; Pst3 is a static pressure at the end of the duct.

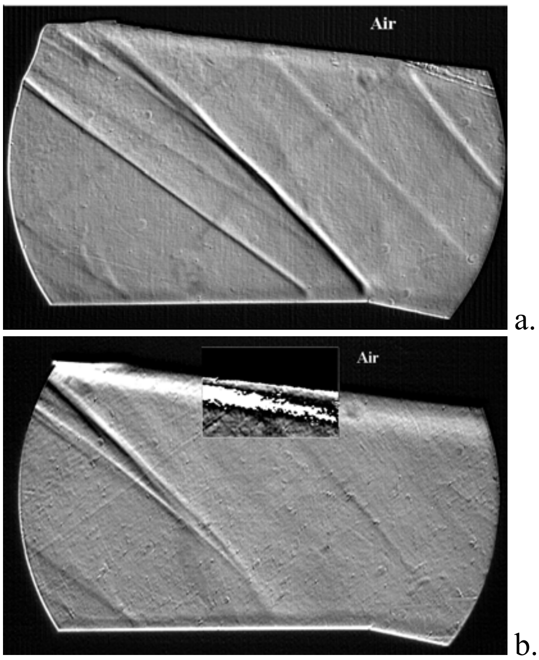

Fig.11. a. Schlieren photo of undisturbed flow in air.
b. Schlieren photo at the surface plasma generation in air.

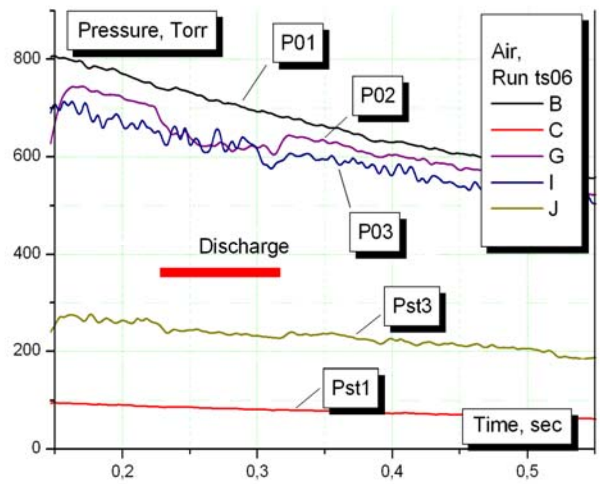

Fig.12. Pressure distribution at plasma generation in air.

The data obtained show that the surface discharge burning upstream of the wedge leads to the shifting of oblique shock upstream and to increasing of the shock angle. The extrusive layer thickness rises up with the distance and reaches the magnitude $h_{pp} \approx$ 7-9 mm in 40-50 mm downstream of the plasma zone. Accordingly, the shock position on the opposite wall is shifted as well. The Fig.12 shows that the stagnation pressure on the axis drops approximately by 8%, while the stagnation pressure downstream doesn't change. The decrease of static pressure means some reduction of pressure loss in a whole duct.

Similar tests were performed in argon and carbon dioxide as the working gases. Comparison of the results is presented in table, where the shock's shift upstream is measured on bottom wall, and the thickness of extrusive layer is measured in 40mm downstream the electrodes position. In contrast to air test some decrease of oblique shock angle is observed for argon and CO2. The extrusive layer thickness was in a range h_{pp} = 4-5 mm in spite of the fact that the specific power release was conserved at the same level. The result of surface plasma action in CO2 is close to that one in argon. In this case a weak flow deceleration takes place without notable total pressure reduction. It should be noted that the flow regime in the whole duct has been modified weakly.

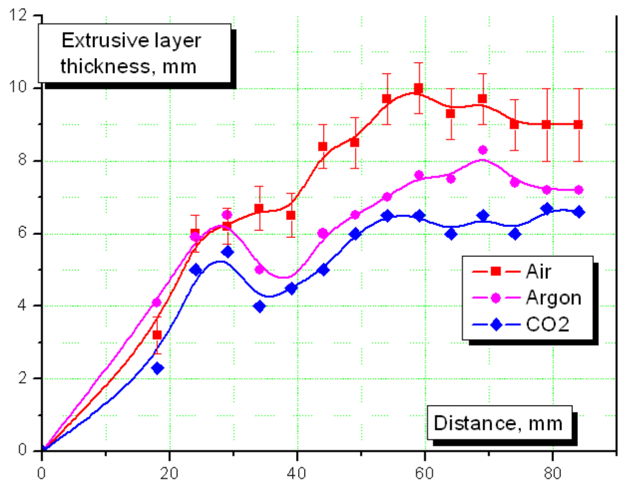

Fig.13. Extrusive layer thickness in dependence on sort of gas.

The comparison of longitudinal dependence of extrusive layer thickness for these cases is shown in Fig.13. It is measured by Schlieren technique, i.e. actually it is a thickness of density irregularity.

Gas	Power, kW	Shock's shift, mm	Extrusive layer thickness, mm	$P_0 2$ and $P_{st} 3$ change, %
Air	1.75	20	8	-8%; -3%
Argon	1.7	5	5	0; -2%
CO2	1.8	10	4	+3%; +7%

The length of direct power release due to Joule heating is about 20-30mm. Here the difference in expansion can be explained by different thermodynamic properties of the gases: $dh_{pp}/dW \sim (\gamma\text{-}1)/\gamma$. Below this line mainly three processes are in competition: cooling with some impaction, turbulent mixing, and extra expansion due to energy relaxation from internal reservoir. Well seen that the discharge in air demonstrates a favorable behavior to control of shocks position in duct-driven supersonic flow.

5 Conclusions

It is clear that an addition of thermal power to gas leads to modification of flow structure. From the other side such an addition can change the parameters of flow significantly and not in the desired direction. Too much power is required to modify a whole flowfield in high-speed dense gas. The efficiency of the plasma influence is very important at the diminishing of the possible penalties. The idea of plasma strong non-uniformity in space structure, non-equilibrium composition and unsteady temporal behavior gives chance to get a quite sufficient effect at technically reasonable level of power release.

The problem of high-speed flow control by non-equilibrium plasma is under consideration in two configurations: DBD effect on transonic shock position and shocks' structure control in duct-driven flow by quiasi-DC near-surface discharge. In both cases a role of relaxation processes is critically important.

It was found that the heat release in DBD can prevent a positive electrostatic effect in BL velocity profile. In case of high-speed flow the VT relaxation can happen mostly downstream the area of interaction, if the effective time is much more than appropriate gasdynamic time. An extra mechanism of the DBD effect amplification is the utilizing of resonant method of DBD supplying when the $St \approx 1$. The result was demonstrated experimentally as a shift downstream the transonic shock over profiled model.

Vise verse to that a slowed relaxation of non-equilibrium air plasma can modify a longitudinal profile of extrusive layer downstream zone of discharge generation. As it was shown experimentally, the application of external magnetic field gives two important benefits. Full or partial stagnation of filamentary discharge by transversal MF increases the efficiency of local deceleration of main flow and increases the reduced electrical field E/n (as the result the plasma occurs more non-equilibrium). Appropriate experimental results on flowfield control by plasma generation near wall are presented. Two techniques have been exploited for observations of the flow structure: the Schlieren shadow technique and pressure distribution measuring. In some important cases the local plasma generation leads to notable flow structure modification in relatively distant zone. Experimentally this item was tested by comparison of data for air (large τ_{vt}), argon (no vibrational excitation) and CO2 (short τ_{vt}).

Some part of the work was funded in 2001-2004 by EOARD (ISTC project 2084p, Dr. John Schmisseur supervision). In 2003-2005 the work in this direction was supported by Program #20 of Presidium of RAS (coordinator Acad. Goremir Cherny).

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