FLOW CONTROL in MODEL SUPERSONIC INLET by ELECTRICAL DISCHARGE

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Abstract. This paper is aimed to present the results of experimental and computational works in a field of supersonic Flow Control by means of near-surface electrical discharge generation. The main objective of this activity is to demonstrate the steering effect of plasma on supersonic flow structure in a compression ramp model. The experiments were arranged in connected pipe configuration (lab-scale).

Introduction.

Comparing with mechanical one the method of high-speed flow control based on plasma deposition possesses, at least, two advantages, namely: inertialess and flexibility (electronic control of magnitude and location). Numerous potential applications may be considered (still extemporized in the most cases) for this technique [1-3]. The paper reports some results of the experimental and computational efforts devoted to plasma effect on supersonic compression ramp performance. The experiments were arranged in connected pipe configuration (lab-scale).

In early 2000s the ability of near-surface electrical discharge was demonstrated to control a supersonic flow structure in a variety of geometrical configurations [3-6] including a compression ramp. The effectiveness of plasma method for flow control critically depends on spatial distribution of power deposition. The realization of required level of gas processing for predefined region is non-trivial technical problem for a high-speed flow. Plasma of electrical discharge appears in more-less homogeneous form at relatively low gas pressure [3-4] limiting the field of application. At the same time the effectiveness of non-uniform plasma was demonstrated at higher gas density [5-6], which was typical for practical aerodynamics. The effect of artificial flow separation behind discharge zone over a plane wall was found out and described in details at the first time [5].

The next important feature of electrical discharge application is that the gas heating occurs not only at the place of electric current location but also downstream of this region due to both recombination and vibrational-translational (V-T) relaxation. Under optimal conditions up to 90% of power deposition can be conserved in vibrational reservoir and dissociation of molecular gas. From the other side this energy can be deposited later to provide more preferential profile of extrusive layer. The idea of using plasma with strong spatial non-uniformity, nonequilibrium composition, and unsteady temporal behavior gives chance to get a notable effect at technically reasonable level of power release. It was shown experimentally that the discharge in air demonstrates some advantage for shocks position control in duct-driven supersonic flow [5-6].

Experimental approach.

The first objective of this activity is to demonstrate the steering effect of plasma on supersonic flow structure on a compression ramp model. The configuration is close to the geometry of a simple two-dimensional inlet of a supersonic air-breathing engine. Surface plasma generation near the inlet wedge is shown in Fig.1 to shift the shock wave upstream. The angle of a new shock and the shock's position depend on the discharge configuration and parameters (the power release has a major relevance but not only).

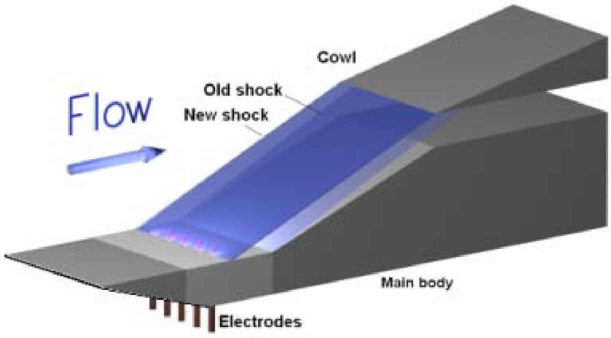


Fig.1. Draft scheme of experiment for demonstration of plasma steering effect in inlet.

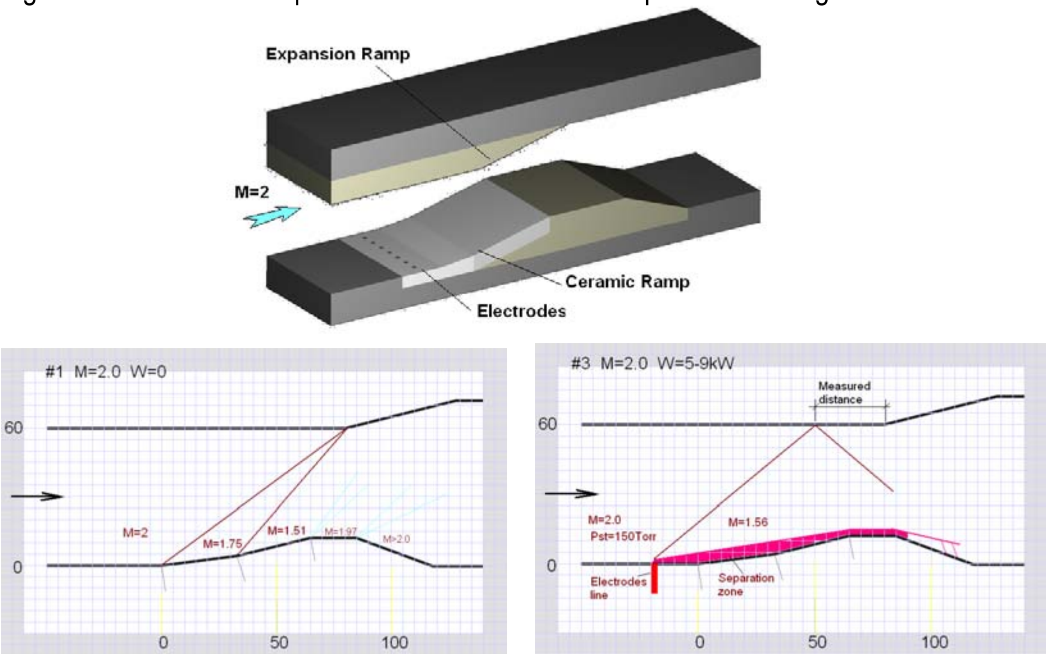


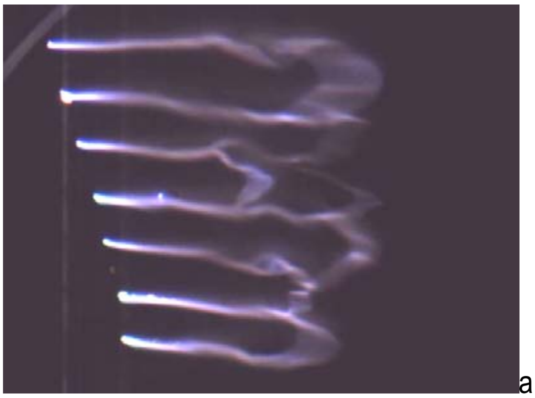
Fig.2. Geometry of the model for M=2 test. Estimation of test result at flow velocity M=2. Plasma off – plasma on.

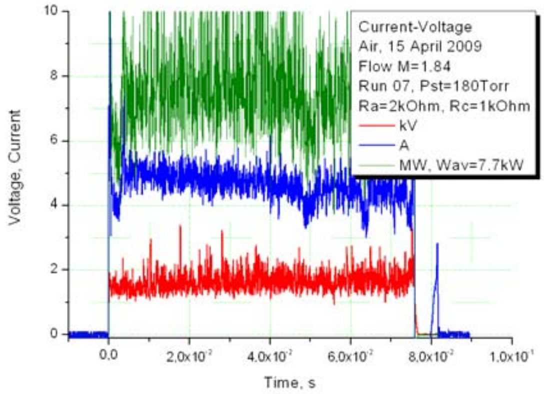
The long terms plans include the experimental, analytical, and computational study of plasma effect on overall performance of the inlet. This part of the work was devoted specifically to study the electrical discharge interaction with supersonic flow for model geometrical configuration in connected pipe scheme.

The test was performed in facility PWT-50 of JIHT RAS [5-6]. Incoming flow in duct with initial height Y_0=60mm and width Z_0=72mm has Mach number M = 2 - 2.5 and static air pressure P_{st} = 100-300Torr. Geometry of the model test is shown in Fig.2. The model consists of two consequent planar wedges $\alpha1=7°$, $\alpha2=14°$ and divergent part. The opposite wall contains the backward wedge $\alpha3=14°$ to avoid the channel blockage. The electrodes' row includes 7 cooper tabs arranged by sequence cathode-anode-…-cathode and locates in X=-18mm upstream the first wedge. All electrodes were flush-mounted and don't affect the flow themselves.

Discharge parameters.

The major properties of the near-surface quasi-DC electrical discharge were described in [5]. The discharge appears in the form of oscillating plasma filaments as it shown in the Fig.3a. Initial electrical breakdown occurs not far from the electrodes location. The individual filaments are blown down due to main flow at velocity a bit less than the core value. The frequency of oscillations depends on flow speed, inter-electrodes gap, and parameters of power supply. In the most cases this value was F=10-30kHz under the experimental conditions. The regulation of power release was performed by means of electrical current change in a range W_{pl}= 3-17kW. The measured maximal translational gas temperature in discharge zone was about $T_g \approx 3000$K, so the V-T relaxation length is expected to be around several centimeters [6]. Typical oscillograms are presented in Fig.3b.


a.



b.

Fig.3. The discharge parameters: a – instant photo, flow from left to right;
b – typical voltage-current-power oscillograms.

Experimental results.

We pose the data below as a demonstration of non-equilibrium plasma advantages for supersonic flow structure control. The measurements were focused on the following three issues: (1) change of the shock wave structure of supersonic flow on compression ramp model; (2) pressure redistribution in vicinity of ramp depending on plasma power; and (3) the flow parameters modification behind the interaction area. In accordance with these objectives the electrical probing, schlieren visualization, and pressure measurements were performed in each test.

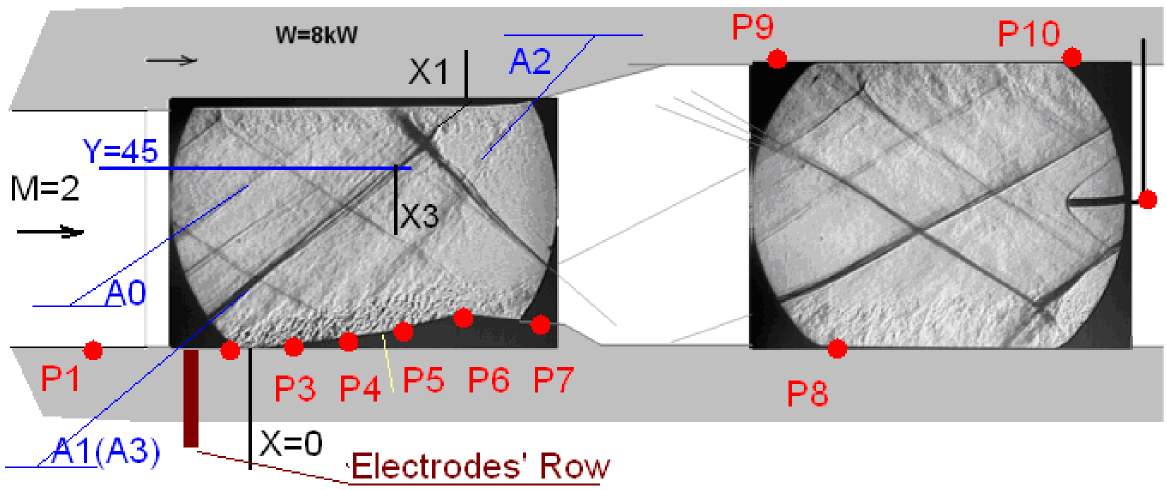


Fig.4. Experiments' arrangement.

The Figures below present the typical experimental data obtained for the model configuration mentioned above. The first picture in the Fig.5 is the schlieren image of undisturbed flow structure. The second picture shows the flow structure when the plasma generator was switched on. The extrusive layer excited by plasma and that the first shock moved upstream are well seen.

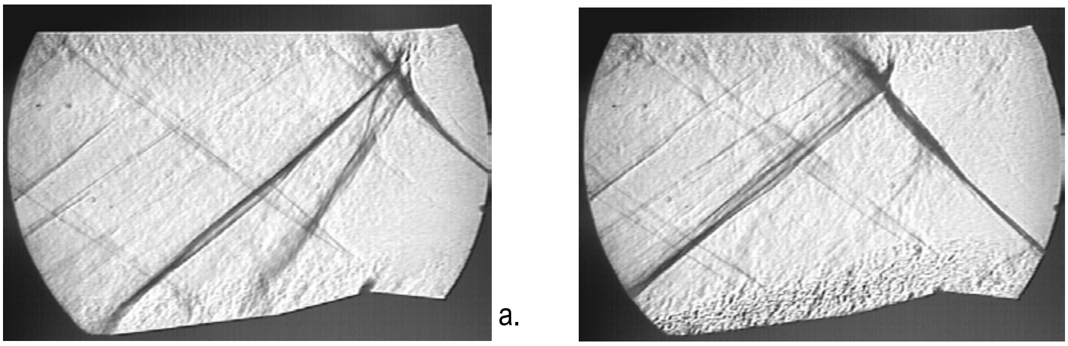


Fig.5 Schlieren picture for (a) undisturbed flow and (b) for plasma generation W=12kW.

Two extra problems were under experimental analysis by means of schlieren-streak technique:

- Duration of transitional mode (time for the new configuration establishment);
- Stability of plasma-induced shock (remember that the discharge is principally unstable).

The generation of new shock structure starts from the first discharge breakdown, SW and thermal cavern formation. The initial stage is shown in instant schlieren image in Fig.6, which was recorded at 60us after the discharge initiation.

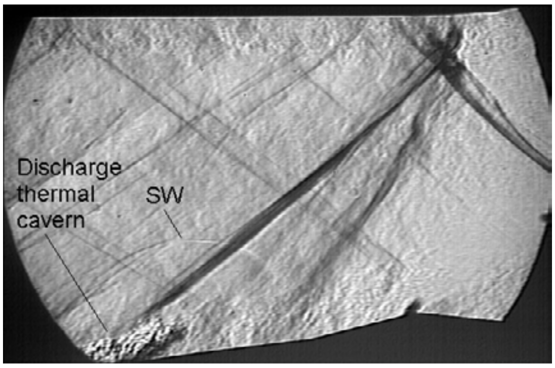


Fig.6. Schlieren image of initial stage of new shock structure formation. Delay 60us.

The new shocks pattern is established in approximately 0.2ms that is well visible in schlieren-streak image, Fig.7. The line of scanning was tuned in the mid section of the channel. The first shock is stabilized in a new position; the second shock almost disappears quickly. A bit more time is needed for a new reflected shock formation. The longest time elapses for the restoration of initial structure after the discharge was switched off.

The period of the discharge oscillation is about 50us, which is less than the shock structure renovation. The schlieren-streak images prove the statement on stability of new shocks position.

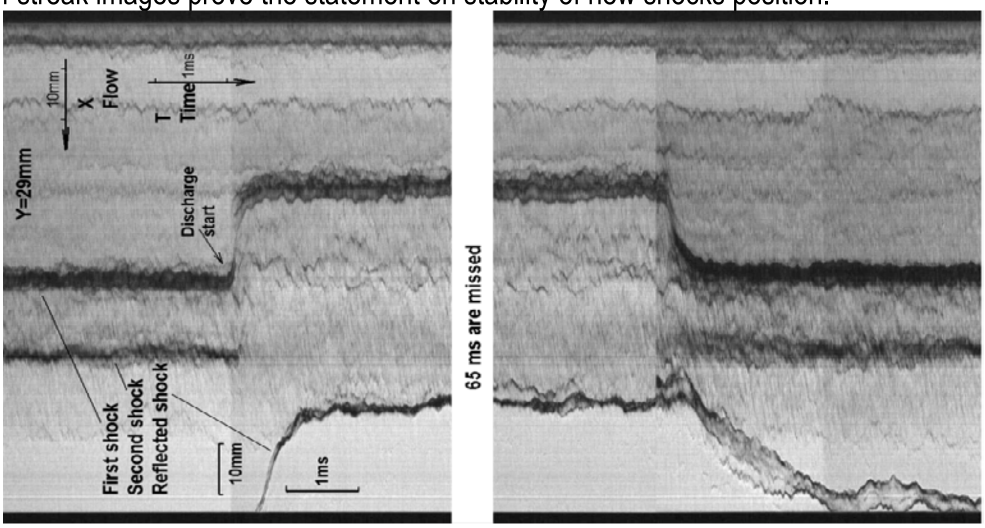


Fig.7. Schlieren-streak image. Y=29mm.

The decrease of shock angle indicates that the conditions for the model flowing around are significantly modified, namely, the pressure losses may be expected less than under initial configuration. The pressure measurements prove this premise as shown in Figs.8 and 9. The integration of the pressure distribution along the model gives the reduction of tangential force in factor 0.7. The Fig.9 presents the data on the total pressure measurements (Pitot tube pressure) across the channel downstream the model location. It may be considered the total pressure rise in the core of main flow, which reflects the reduction of the pressure losses in the model associated shocks.

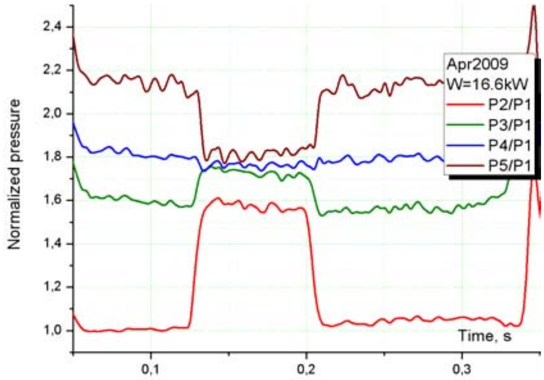


Fig.8. Static pressure redistribution on ramp under plasma generation.

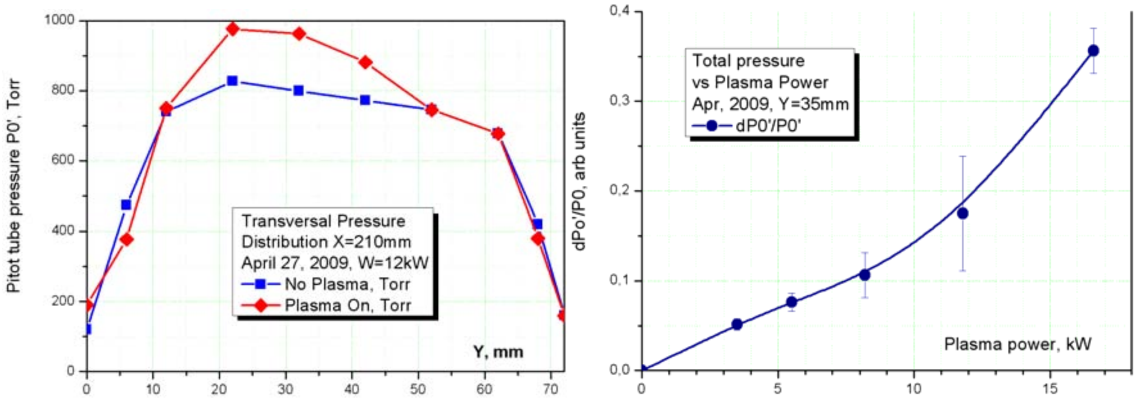


Fig.9. Plasma effect on total pressure downstream.
Y-redistribution; Effect vs plasma power.

The First Shock Angle and Position vs Plasma Power

The schlieren images allow to recognize the details of the flow structure (see Fig.4). The first shock position X3 was measured at Y=45mm (top wall has coordinate Y=60mm) due to irregular shock reflection on the wall. The shock angle A1 was measured as an average angle in a range from Y=10mm to Y=45mm. The shock's position X1 corresponds with the point of regular reflection. It is calculated based on A1 and X3. The initial angle A0 is the characteristic angle corresponding with the main flow Mach number. It is a bit deviated from series to series.

The Fig.10 presents graph of the first shock angle depending on the plasma power release at two values of initial Mach number. The calculated results for M0=2 is shown here as well. The behavior is unstable at low level of plasma power: dashed line connects the experimental point here. The accuracy of angle measurement is not worse than ±0.5°.

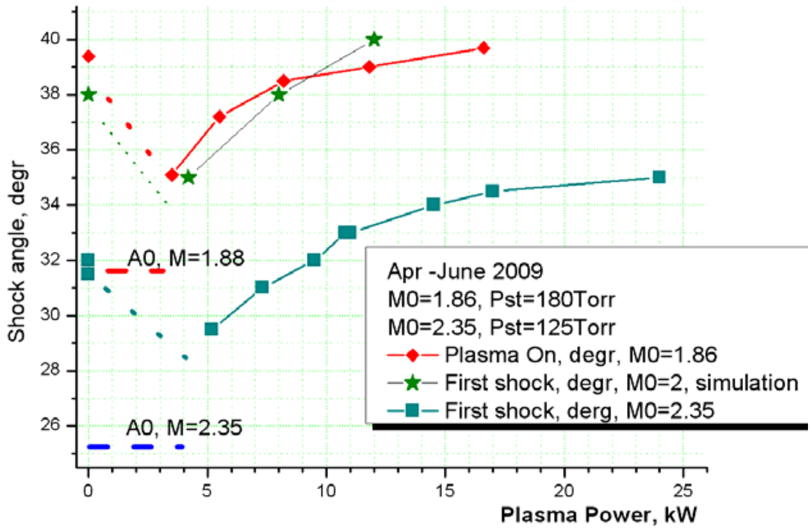


Fig.10. The first shock angle vs plasma power.

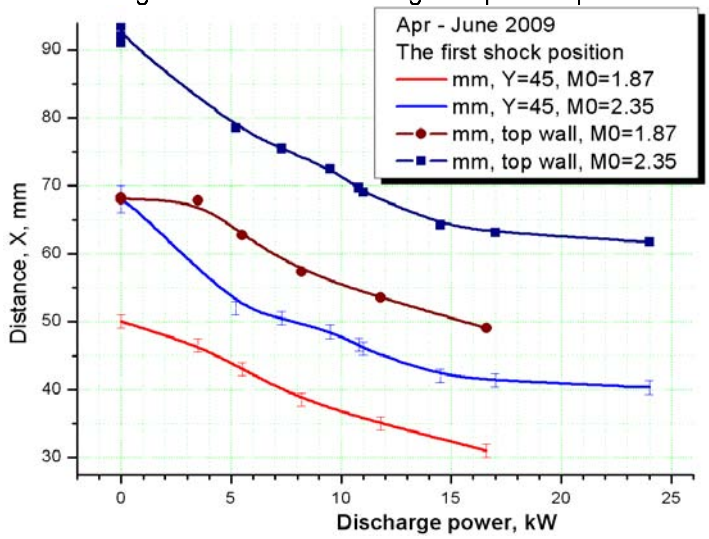


Fig.11. The first shock position at Y=45mm and on top wall vs plasma power.

The next graphs in Figure 11 shows the values of shocks position at Y=45mm and on the top wall. The following statement can be written based on these results:

- Zone of effective regulation of the shock position is covered by the power range W_{pl}=3-15kW. Following increase of the power can be useless.
- In this experimental series the range of regulation only a bit higher than the wedge-electrodes distance X=-18mm.
- In this experimental approach the shock at M0=2.35 falls to the same position as for M0=1.87 at plasma power W_{pl}=10-12kW.

The data obtained show that the surface discharge burning upstream of the wedge leads to upstream shifting of the root part of oblique shock. At relatively small power release the angle of the first shock is decreased significantly. The increase of the plasma power leads to rise of the first shock angle as it is presented in Fig.10. The second shock occurs much weaker than under initial conditions. The power release below the value W_{pl}<3kW causes an unstable behavior of the first shock. Such type of plasma-flow-model interaction can be called as “plasma screening” [5]. Downstream of this region three main processes are in competition: cooling, turbulent mixing, and extra expansion due to energy relaxation from internal reservoir.

Conclusions.

We advocate a point of view that in aerospace applications the plasma technology makes a sense for a correction of flow-field and support of high-speed flow regulation under the off-design operation modes. A theory and the lab-scale experiments prove a hope on effective, inertialess, and adjustable control of the flow structure and gas parameters. In the most cases this method is much more effective than mechanical one. In some cases there are no other methods to achieve a required result.

One of possible field for a practical interest is the plasma steering effect in high-speed inlet configuration. The generation of surface localized discharges in a high-speed flow makes possible substantial change the structure and parameters of the flowfield. This work examined several aspects of the problem, namely, the effect of discharge on supersonic flow structure and parameters; control of flow parameters in inlet's configuration; reduction of pressure losses; etc. For the better understanding of the problem the experimental findings were compared with the results of numerical simulation.

The transversal electrical discharge affects the flow similar to a soft wedge, whose angle depends on the electrical power release. At exceeding of the value about $W/P_{st}\approx 10\times z$ W/Torr, where z is the discharge region depth, the flow separates downstream with subsequent attachment or without it. The discharge generation is accompanied by the formation of an oblique shock, whose amplitude, angle, and position allows regulation with the aid of electrical parameters variation.

Surface plasma generation near the inlet wedge is shown to regulate the angle of the first shock and to shift the shock wave in respect of the initial position. The angle of a new shock depends on discharge power input in typical range

$$w=W_{pl}/(Z\times P_{st})=(2\div 10)\text{kW/Bar}\times\text{cm}$$

where w – is reduced plasma power, Z – is the channel width. In the case of air a huge gradient post-plasma extrusive layer is observed that is in accordance with an idea of the mechanism of slowed V-T relaxation. This layer "screens" the contoured model leading to some reduction of the pressure losses in the channel. The thickness and the length of this layer depend on static pressure in test section. Despite of an unstable behavior of the discharge the shocks' position was stable, predictable, and allows regulation by means of discharge parameters. The experiments and CFD simulations have demonstrated a promising ability of electrical discharge to improve the inlet's performance.

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