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Plasma-Jet for Flow Control

N. Ardelyan, V. Bytchkov, D. Bytchkov*, A. Chernikov, K. Kosmachevsky, and M. Sablin*

Lomonosov Moscow State University

* FSUE Moscow Radiotechnical Institute

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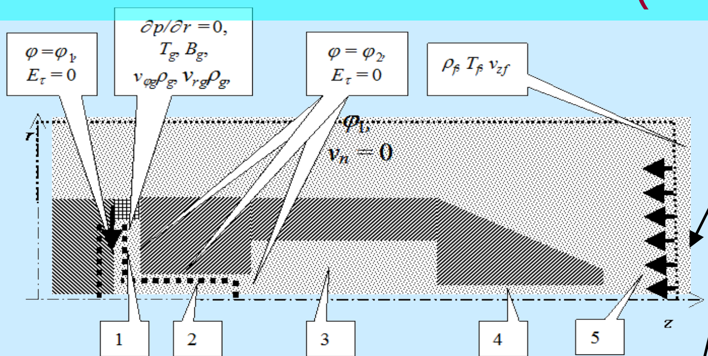
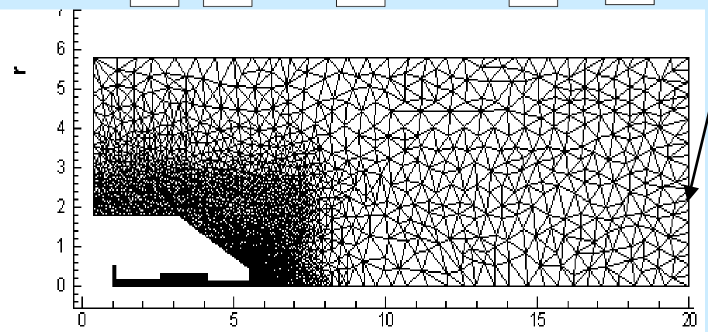
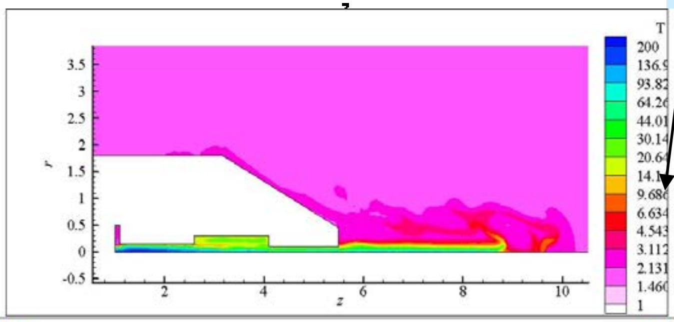
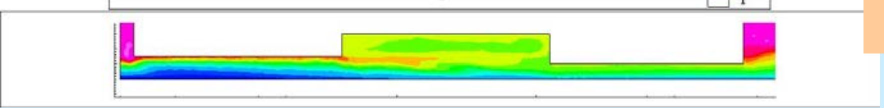
Modeling of plasma generator with cylindrical cavity channel explaining experimental results of ITAM (investigations 2000 - 2002)

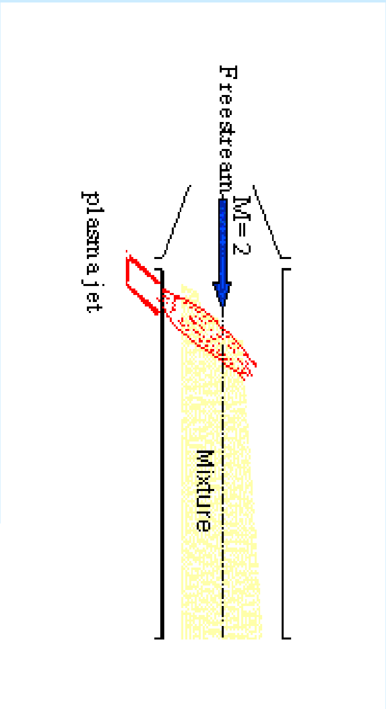


Plasma jet, Nitrogen, mass flow m_f = 0.7 g/s, power input P=7.5 kW , free stream Mach number, M=2.

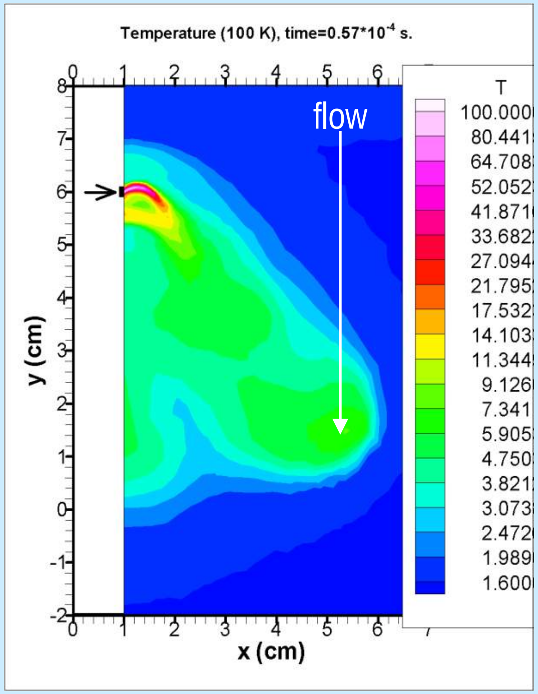








Schematic of gas activation with row of plasma generators



Isotherms (θ=180 °;θ= 45°) of planar plasma jet injection into incoming flow

Plasma generators with divergent nozzles are promising new devices

- They create high enthalpy plasma flows that are useful for fabrication of various materials.
- They are simple to manufacture and operate, and allow quick modification and access.
- But the operating power of conventional generators is very high ~500 kW; this is inappropriate for aerodynamics and propulsion.
- Plasma generators characteristics at powers 10-20 kW have yet to be analyzed and their plasmadynamic properties are to be understood.
- This motivates our computation studies directed the plasma aerodynamics applications with a help of these plasma generators.

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Magneto-Plasma Compressor (MPC)

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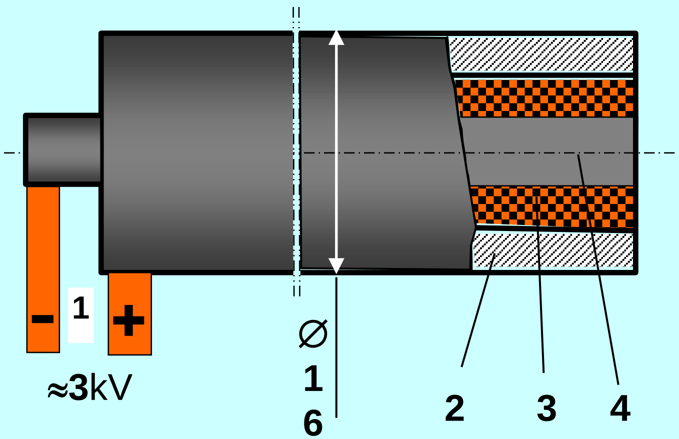

Fig. 1. Schematics of the pulse plasma generator (MPC)
1 – input energy 200-250 J, τ≈50 mcsec,
2 – anode, 3 – isolator, 4 - cathode

An initial velocity of plasma formation reaches 2 km/s and plasma parameters in a cumulating zone are the following: temperature is **T** =(18-20)×10^3 **K** and an electron concentration is n=5 ×10^16 - 10^17 cm -3. Parameters of a power source are the next: charge capacity - 50 μF, voltage – 3 kV and it corresponds to 225 J of a stored energy. A duration of the first discharge current half- period is 20 μs (a duration of the first quasi period of a discharge current is approximately 50 μs).

g. 1.1.2. Input discharge energy (single

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Plasma jet installation and photos of the plasma jet (E=200-250J) in the channel

a – schematics of the flow field

1 – pulse plasma generator,

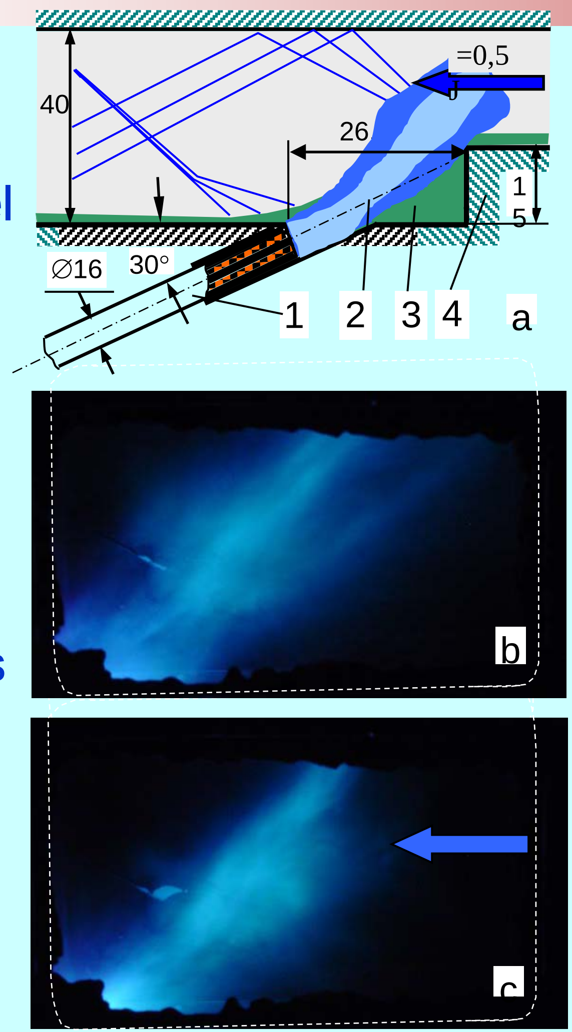
2 – plasma jet,

3 – separation zone,

4 – reverse step,

b – plasma jet in motionless air,

c – jet in a M=2 air flow (P_t=0.3 MPa)



A scheme of MPC-plasma jet installation in a test channel is shown and a direction of MPC axis was chosen basing on arguments of maximal plasma penetration depth into the airflow and to obtain long-lived plasma area. Photos of the discharges with and without airflow demonstrate the same pictures of airflow/plasma interaction and confirm that the penetration of the plasma does not depend on airflow velocity in these test conditions.

System of plasma aerodynamic equations (Lagrangian form)

$$\frac{\mathcal{D}\vec{x}}{\mathcal{D}t} = \vec{u},$$

$$\frac{\mathcal{D}}{\mathcal{D}t}\frac{1}{\rho} - \frac{1}{\rho}\nabla\cdot\vec{v} = 0, g = p - \nu\nabla\cdot\vec{v},$$

$$\rho\frac{\mathcal{D}\vec{v}}{\mathcal{D}t} + \nabla g - \nabla\cdot\left(\mu U\right) = 0, U = \left[\nabla\vec{v} + \left(\nabla\vec{v}\right)^{*}\right], \ \nu = \lambda - \frac{2}{3}\mu,$$

$$\rho\frac{\mathcal{D}\varepsilon}{\mathcal{D}t} + g\nabla\cdot\vec{v} - \frac{1}{2}\mu U\cdot\cdot U + \nabla\cdot\vec{W} - f = 0, \vec{W} = -\theta\nabla T,$$

$$p = P\left(\rho,t\right), \varepsilon = \mathrm{E}\left(\rho,t\right), f = f\left(\rho,t\right).$$

Inflow to the channel

p: $\frac{\partial p}{\partial n} = a_1$; ρ, T: S(entropy) $=$ const;

v_n: mass flow rate $\rho v_n =$ const.

Outlet flow

$\frac{\partial f}{\partial n} =$ const.

Plasma properties at T = 5000-10000 K

In the case of nitrogen

$$N + N \leftrightarrow N_2, \ e + N^{+} \leftrightarrow N;$$

$$N^2 / N_2 = F1(T), \ (N^{+})^2 / N = F2(T), \ \rho / m_N = N + 2N_2$$

Modeling of plasma jets for Flow Control

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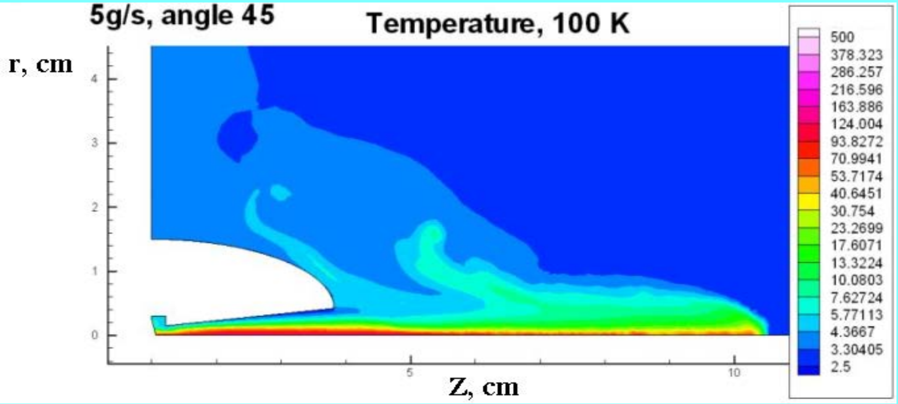
We apply powerful computational method :

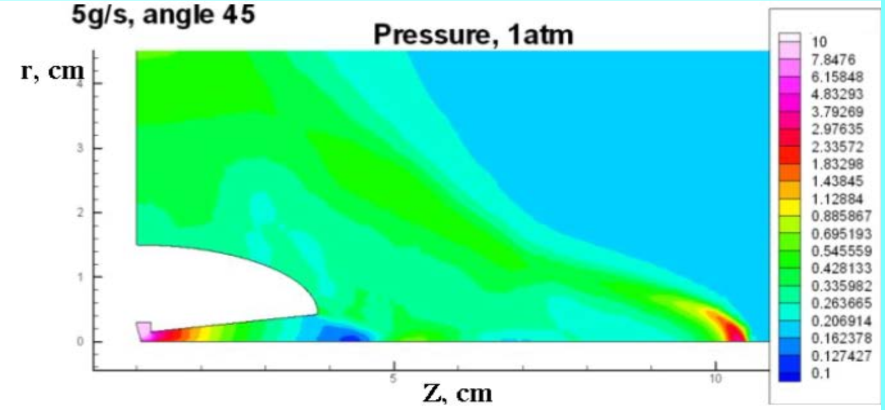
The free Lagrange method based on completely conservative implicit difference scheme and adaptive, automatically remeshing unsructured triangular mesh.

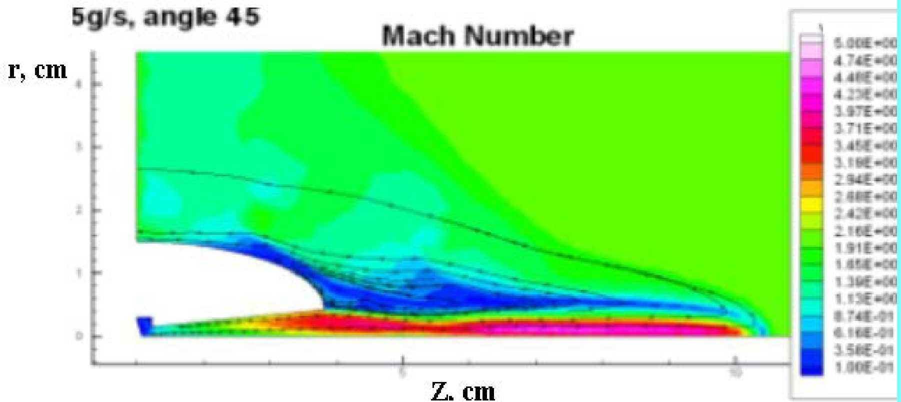
Large and medium vortices, heat, momentum, and mass transfer processes are effectively modeled.

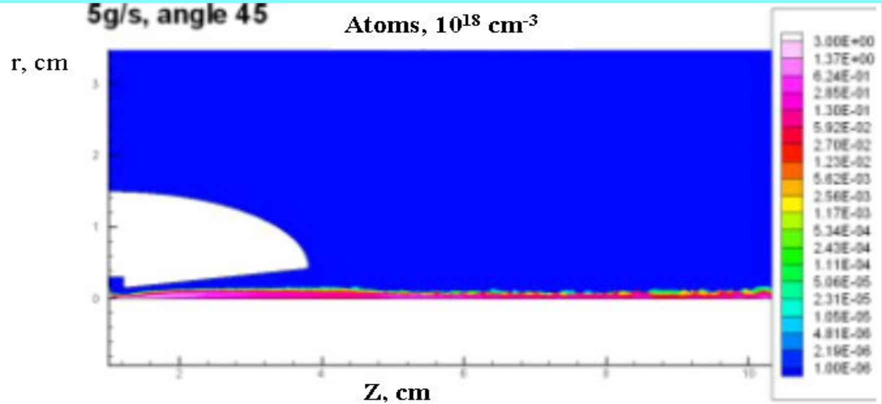
Plasma jet interaction with counter flow

M=2, P=0.2 atm, W=13 kW, gas mass flow rate 5 g/s.









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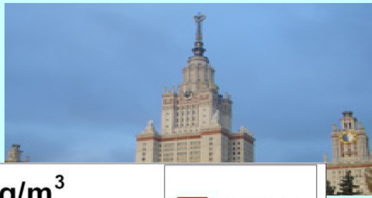
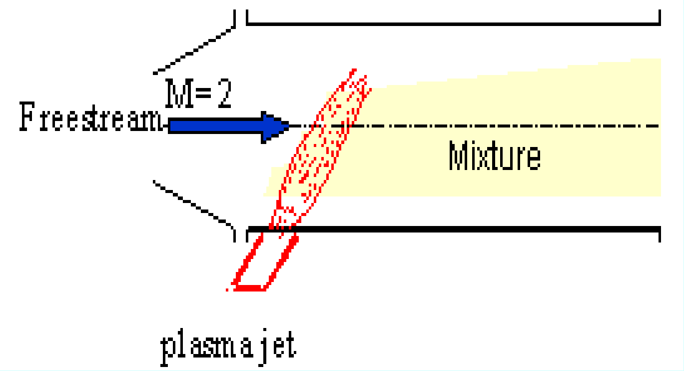
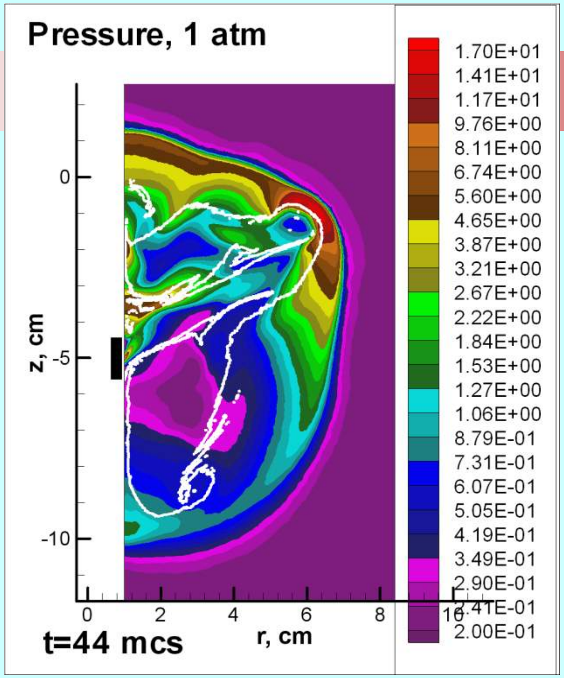
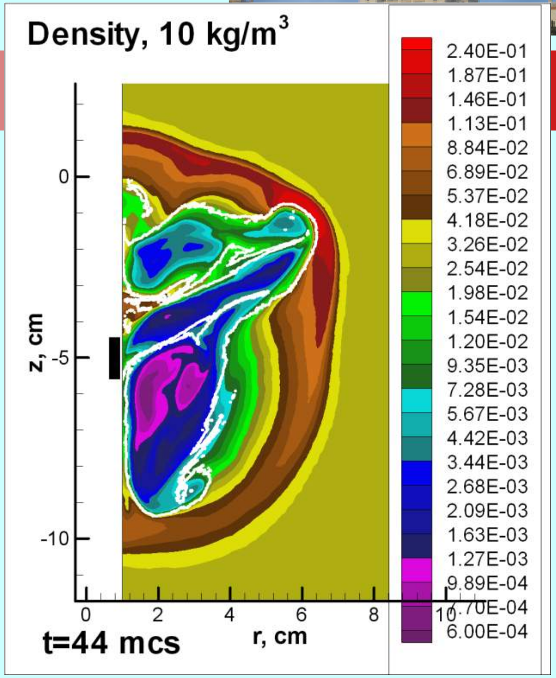




Plasma jet from a slot created by a row of plasma generators



Plasma Jet interaction with the cross flow at (θ=135^{0}). Pressure distribution at the plasma jet entering the incident gas, consumption of a gas 0.2 g/s, inflowing gas pressure 0.2 atm, plasma generator power 15 kW. White area is a boundary of the plasma region.



Plasma Jet interaction with the cross flow at (θ=135^{0}). Density distribution at the plasma jet entering the incident gas, consumption of a gas 0.2 g/s, inflowing gas pressure 0.2 atm, plasma generator power 15 kW. White area is a boundary of the plasma region.

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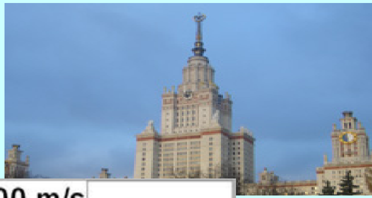

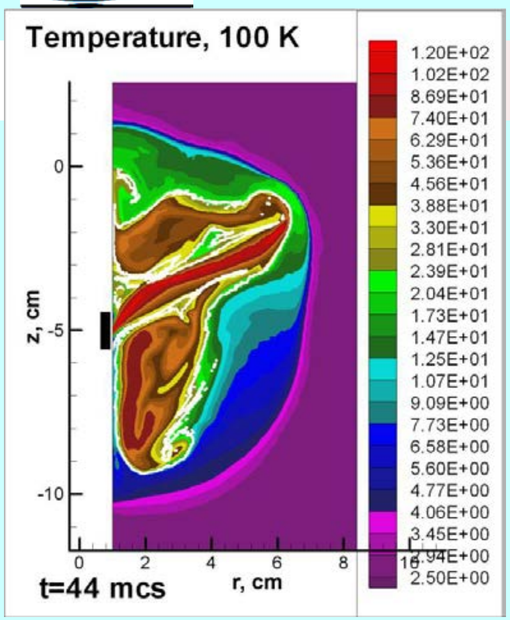

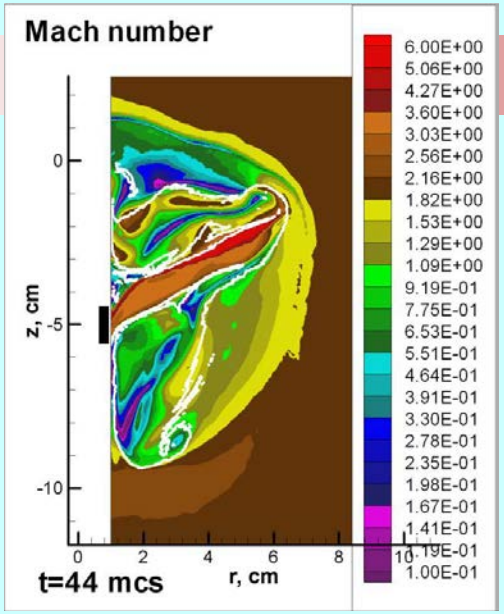

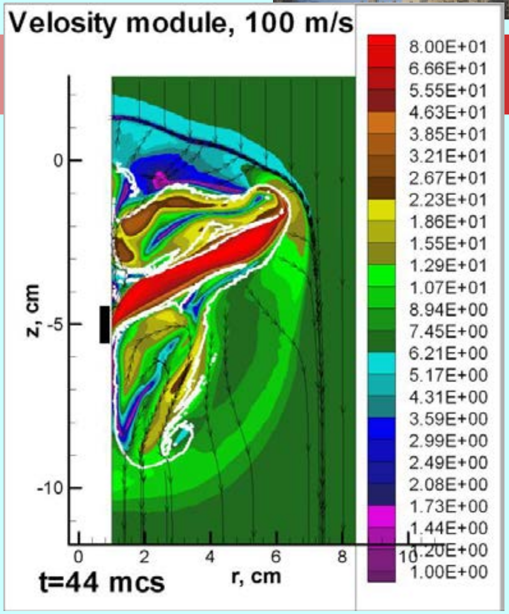

Plasma Jet interaction with the cross flow at $(\theta=135^0)$. Temperature distribution at the plasma jet entering the incident gas, consumption of a gas 0.2 g/s, inflowing gas pressure 0.2 atm, plasma generator power 15 kW. White area is a boundary of the plasma region.

Plasma Jet interaction with the cross flow at $(\theta=135^0)$. Mach number distribution at the plasma jet entering the incident gas, consumption of a gas 0.2 g/s, inflowing gas pressure 0.2 atm, plasma generator power 15 kW. White area is a boundary of the plasma region.

Plasma Jet interaction with the cross flow at $(\theta=135^0)$. Absolute value of a velocity distribution at the plasma jet entering the incident gas, consumption of a gas 0.2 g/s, inflowing gas pressure 0.2 atm, plasma generator power 15 kW. White area is a boundary of the plasma region.

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Simulation of the plane nitrogen plasma jet in the air cross flow: (M=2, P=0.2 atm, W=13 kW, at the gas mass flow rate 5 g/s, angle 150°).

- Pictures: T8, T18, T44, RO44, P44, Vmod44, Mach44.
- Movie: T, RO, P, Vmod, Mach, Jet_mesh.

Angle 135°, P, T, RO, Vmod, Mach, Jet_mesh.

Let us discuss possible force effects created by the plasma jets. N. Zhukovsky theorem determines a force influence of a potential flow on a flown around body of an arbitrary form. For example if a cylinder [11] is streamlined by an ideal incompressible liquid then it experiences a force action, normal to velocity in infinity and equal to a product of this velocity V_∞ , circulation and flow density ρ :

$$F = \rho \cdot \Gamma \cdot V_\infty \cdot l \qquad \Gamma = 2 \cdot \oint \bar{V}\, d\bar{l}$$

Looking at the Fig., one can understand that jets greatly modify a flow around a surface creating additional lifting forces. They also create vortex structures which can modify trailing wingtip vortexes, and their influence will be greater than in case of dielectric barrier discharges, since the energy of jets is higher and their momentum is larger than those of DBD discharges. The MPC plasma jets can be the best solution for creation of the plasma impact on the flow.

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Conclusions

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We have presented a preliminary analysis of a possible applicability of plasma jets to flow control problems. We have presented an effective type of plasma jets- magneto plasma compressor, experiments with which show its high penetration into a flow and the possibility of application in the flow control tasks.

We presented the external/internal theoretical-computation analysis of the plasma jet - crossflow interaction for conditions of already known and of planning experiments. Derived equations allowed application of the implicit free-Lagrange method to carry out computations. Our computations show the complex and non-homogeneous structure of the flow for the structure of a flow outside the plasma generator, which is different for different types of plasma generator geometries. Our results are in the qualitative agreement with results of known experiments for divergent plasma jets entering the dead gas. They facilitate interpretation of new experiments, particularly the relative roles of plasma and gasdynamic processes.

This preliminary analysis is necessary gasdynamic part of plasma- jet applicability for flow control investigation problems. Obtained results show that the plasma jet generators could be more prospectus for flow control of subsonic and supersonic streams than that DBD.

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Acknowledgments

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Thank You for Attention