

# STATIONARY ELECTRIC ARC PLASMA GENERATOR FOR INFLUENCING ON SUPERSONIC GAS FLOW

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## **Abstract**

Studies of plasma jet interaction with cross flows has been made for development of the concept of enhancing of combustion and ignition at application of plasma jets. A computer simulation of a cross flow nitrogen plasma nitrogen jet from the divergent plasma generator in nitrogen has been carried out. This model involves a realistic equation of state, plasma radiation associated with plasma formation inside the plasma jet as well as coupling between the internal nozzle with external flow fields. Our model facilitates the application of the implicit free-Lagrange method for carrying out of computations, which have been carried out for jet injection angles  $135^\circ$  into the cross flow. These show the complex and non-homogeneous structure of the flow. They represent the necessary step in understanding of applicability of the divergent plasma jets for propulsion enhancement.

## **Introduction**

The concept of plasma enhancing combustion and ignition by applying weak ionization is being investigated at a number of laboratories, recently<sup>1</sup>.

Calculations simulating gas discharge devices relate to composition of thermal plasmas in air, nitrogen and hydrogen as a function of gas temperature<sup>2-3</sup> show that for typical plasma jet temperatures in the range  $5000-10,000^\circ$  K the conditions are already sufficient for ignition of flammable mixtures and the role of combustion enhancing by plasma chemical mechanisms or by plasma dynamic processes becomes of interest. Our analyses show that plasma jet – supersonic flow interaction processes can easily stimulate the fuel activation.

Solving this problem requires considering interaction of the plasma jet with a cross flow. In a two-dimensional approach we model a row of plasma generators with the divergent nozzle interacting with the flow at some angle ( $0-180^\circ$ ) to the flow, see Fig.1<sup>4</sup>.

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In this our simulation as in<sup>4,5</sup>, the gasdynamic equations are coupled with the 2-D Maxwell equations, and the plasma dynamics equations, accounting for ohmic heating and radiative plasma cooling. A Lagrange method based on a completely conservative implicit difference scheme with an adaptive triangular mesh<sup>6</sup> is applied. This was effective in modeling the coupling of the internal and external flows inside and outside the counterflow jet and its nozzle<sup>5</sup>. This approach is applied in this investigation of interaction of divergent plasma jets with cross flows.

In the present work we consider the construction of the plasma generator with the divergent inter electrode channel where the minimum nozzle diameter is 3 mm. The half angle is 6°. The nozzle length along the axis is 30 mm. The cathode diameter is 4.5 mm. The half angle of the conical cathode is 75°. The distance between the cathode to the nozzle is 1.7 mm. The transmitting area in channels is equal to the transmitting area in the nozzle critical cross section. In the initial part of the nozzle takes place the nitrogen inflow to the plasma generator. The range of the plasma generator power is 10-15 kW, the gas consumption range is 0.2 g/min-0.2 g/s. The energy input to the gas takes place mainly at a distance of 5 mm before the cathode.

The divergent plasma jet was chosen for its prospective properties shown in<sup>7,8</sup>

### **Plasma generators injecting plasma jet to a crossflow**

The model is based on the following system of radiating plasma electrodynamics equations verified in<sup>2,3</sup>

$$\partial\rho/\partial t + \text{div}(\rho\mathbf{v}) = 0, \quad (1)$$

$$\rho \, d\mathbf{v}/dt = - \mathbf{grad} \, p,$$

$$\rho \, d\varepsilon/dt = - p \, \text{div} \, \mathbf{v} + j^2/\sigma - q,$$

$$\mathbf{rot} \, \mathbf{E} = - \partial\mathbf{B}/\partial t,$$

$$\mathbf{rot} \, \mathbf{B} = \mu_0 \mathbf{j},$$

$$\text{div} \, \mathbf{B} = 0,$$

$$\mathbf{j} = \sigma \mathbf{E},$$

where  $\rho$ ,  $p$ ,  $\mathbf{v}$ ,  $\varepsilon$  are the plasma (gas) density, pressure, velocity, and internal energy;  $\sigma$  is the electric conductance of the gas and plasma,  $q$  is the specific power of plasma thermal radiation,  $\mathbf{E}$  is the electric field intensity,  $\mathbf{B}$  is the magnetic field induction,  $\mathbf{j}$  is the electric current density, and  $\mu_0=4\pi \cdot 10^{-7}$  H/m. The unsteady cylindrically symmetrical approximation with respect to the gas and plasma rotation was applied:  $\mathbf{v} = (v_r, v_\varphi, v_z)$ ,  $\mathbf{B} = (0, B_\varphi, 0)$ ,  $\mathbf{j} = (j_r, 0, j_z)$ ,  $\mathbf{E} = (E_r, 0, E_z)$ ,

$\partial/\partial\varphi = 0$ ; the subscripts  $r, \varphi, z$  correspond to the radial  $r$ , azimuth  $\varphi$ , and axial coordinate  $z$ . The plasma equation of state can be expressed as

$$p = \alpha \rho k_B T / m_{mol}, \quad \varepsilon = p / [\rho(\gamma - 1)], \quad (2)$$

where  $\gamma$  is the adiabatic exponent,  $k_B$  is the Boltzmann constant,  $T$  is the plasma temperature,  $m_{mol}$  is the initial gas molecular mass, and factor  $\alpha$  takes into account the free species number changes resulting from chemical reactions (primarily dissociation and ionization). Functions  $\gamma = \gamma(p, T)$ ,  $\alpha = \alpha(p, T)$ ,  $\sigma = \sigma(p, T)$  and  $q = q(p, T)$  for nitrogen plasmas were computed preliminarily and approximated on the basis of data in Refs. <sup>2-3</sup> Calculations first assumed  $\alpha = 1.1$  and  $\gamma = 1.4$ , as in <sup>4,5</sup> but changed in subsequent in later parametric variations of the temperature  $T$ .

The computation region included both the regions inside the plasma generator and outside the model. No-slip boundary conditions on the walls were assumed for plasma and gas and  $\partial/\partial r = 0$  was assumed on the axis of symmetry. The gas input azimuth and radial velocities  $v_{\varphi 0}, v_{r0}$  were determined via gas density  $\rho_0$  from the given gas flow rate  $m'$  and areas of the inflow tangent orifices  $F_\tau$  and of the circular input slot  $F_s$ :  $v_{\varphi 0} = m' / (\rho_0 F_\tau)$ ,  $v_{r0} = m' / (\rho_0 F_s)$ . The input gas temperature  $T_0 = 300$  K. Conditions  $p = p_f$ ,  $v_z = -v_{zf}$ ,  $T = T_f$  on the right-hand boundary defined the supersonic ambient flow. Conditions on the left-hand boundary and on the peripheral boundary provided a free exit of the fluid.

The entire left-hand wall inside the plasma generator had electric potential  $\varphi_1$ ; in the slot where the gas is injected, the condition on the magnetic field defined via the total discharge current  $I$  was applied:  $B_0 = \mu_0 I / (2\pi r_0)$ , here  $r_0$  is the corresponding radial coordinate. All the remaining walls had electric potential  $\varphi_2$ . Details of computations in case of internal problem are presented in <sup>5</sup>. To expedite the computations, a small background conductance  $\sigma^* < 10^{-3} \sigma_{max}$  was assumed to be in the cold gas; here  $\sigma_{max}$  is the highest value of plasma conductance in the electric current channel. The computed distribution of electric current in the rest of the channel proved to be practically independent of the fluctuations of the plasma conditions (see below). This is a result of the nitrogen weak plasma conductance dependence on plasma pressure and temperature in the parametric region of interest. This allowed us to "freeze" this distribution and to avoid its expensive recalculation during the computations. So we transformed the electrodynamic problem to the problem of the gas heating in the channel.

Preliminary calculations corresponded to the conditions of <sup>7,8</sup> when the plasma injection was realized to dead air at atmospheric pressure at temperature 300 K. Initial density is

determined from the energy of state of the ideal gas, the velocity of inflow is determined by the data of the consumption.

Special calculations were made on the divergent plasma generator injection to a gas at ( $\theta=180^\circ$ ). They are necessary<sup>4</sup> to determine the distribution of parameters over the jet cross section at the outlet for the solution of the cross flow jet interaction at angles ( $0<\theta<180^\circ$ ).

In Fig 2-6 one can see the distribution of main parameters of the divergent plasma entering the gas at ( $\theta=180^\circ$ ) the gas consumption 2 g/s. pressure of the oncoming flow  $P=0.2$  atm. at the plasma generator power 15 kW, typical time in calculations  $10^{-4}$  s. It is 2-D solution of the plasma-gas flow problem, including the internal and external problem as a whole. In this case we use the information on thermal conductivity and viscosity characteristics, since the temperatures in the plasma generator are high. As one can see the distribution of temperature, pressure and density is non homogeneous over the nozzle's exit..

About 10 calculated points in the outlet channel cross section of the plasma generator were used for coupling plasma generator internal nozzle flow with the external flow as in our counterflow jet study<sup>5</sup>.

In solution of the jet-cross flow interaction at angles ( $0<\theta<180^\circ$ ) the jet outside the plasma generator is considered to be flat, it models a row of nearly placed plasma generators. The parameters of the jet at the outlet to the cross flow are taken from the calculations for ( $\theta=180^\circ$ )<sup>4</sup> Such formulation allows to clarify characteristics of the jet interaction with the cross flow, spatial distribution of gas parameters distribution and peculiarities of the jet influence on oncoming flow (presence of shock waves, dependence on outflow angles).

In this case we do not consider the influence of the viscosity and thermal conductivity outside the convergent nozzle in the cross flow since their influence at typical gasdynamic times and external temperatures is small.

Questions of turbulence are not considered on this study of investigations. In this studies we did not consider dissociated and charged plasma properties since this question has been analyzed in<sup>5</sup> it was shown there that nitrogen atom concentrations are of about  $10^{18}$   $\text{cm}^{-3}$  in conditions of interest for the combustion.

### **Discussion of obtained results**

Results for three cases have been obtained.

Obtained results of the divergent plasma get parameters at injection to dead air qualitatively agree with experimental data<sup>7,8</sup> in temperatures distribution (0.3 - ~45 kK) over the

cross section at the same distance from the electrode and the same plasma generator power  $W \sim 50$  kW. Concentrations of electrons were comparable with those of <sup>8</sup>.

At Fig.2-6 we present characteristics of the profiled plasma jet at the nozzle exit outflowing at  $180^\circ$  into nitrogen. Results of calculations show that at time moments  $(4 - 10) \cdot 10^{-4}$  quasi-stationary situation is realized.

At Fig. 7-11 we present results for a divergent plasma jet coming out from the nozzle at  $(\theta=135^\circ)$ . The jet screens a flow and a shock wave is formed in oncoming flow. The oncoming flow turns at the shock and flows along the jet. A region screened by the jet is formed behind the jet. Temperature picture shows appearance of a cluster of highly heated gas.

In general temperatures and flow velocities in the place of jet-flow are consistently higher than in the case of the jet from the plasma generator of <sup>5</sup> (a plasma channel with the barrel-type cavity).

### **Summary and Conclusions**

We presented the external/internal theoretical-computation analysis of the divergent plasma jet - crossflow interaction for conditions of already known and of planning experiments. This preliminary analysis is necessary gasdynamic part of plasma-jet applicability for ignition-combustion investigation problems.

Equations for plasma inside and outside a channel including transport, chemical and ionization processes were applied. Derived equations allowed application of the implicit free-Lagrange method to carry out computations.

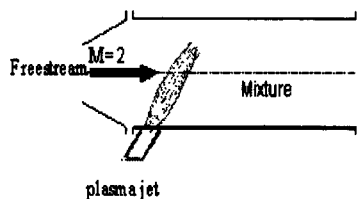
Our computations show the complex and non-homogeneous structure of the flow for the structure of a flow outside plasma generator, which is different for different types of plasma generator geometries. Obtained results show that the divergent plasma generator could be more prospectus for fuel ignition and combustion in the supersonic flow than that considered in <sup>4,5</sup>. Our results are in 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.

### **Acknowledgments**

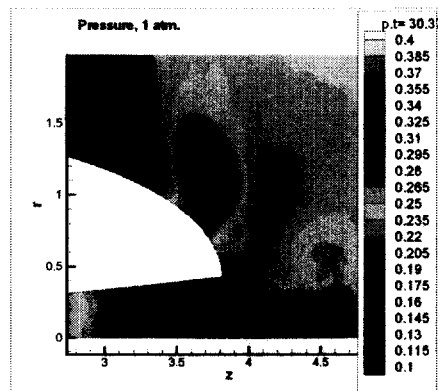
The authors wish to acknowledge EOARD program support under the Project # 2449 p.

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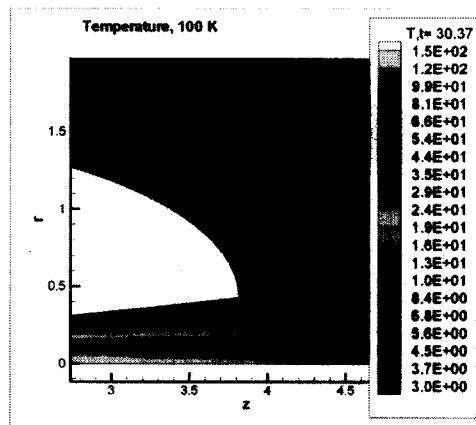
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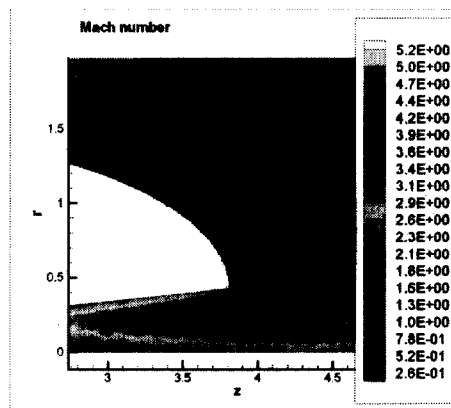
**Fig.1** Plasma jet from a slot created by a row of plasma generators



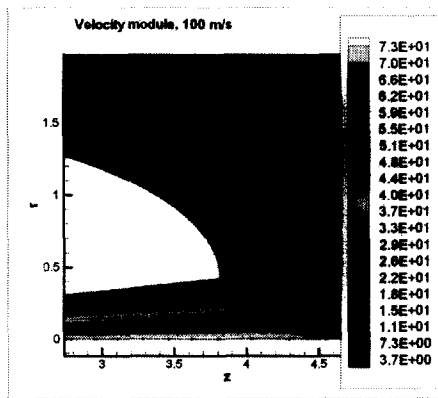
**Fig.2** Pressure distribution at the divergent plasma jet entering the incident gas, consumption of a gas- 0.2 g/s, inflowing gas pressure- 0.2 atm, plasma generator power -15 kW, time - $30 \cdot 10^{-4}$  s



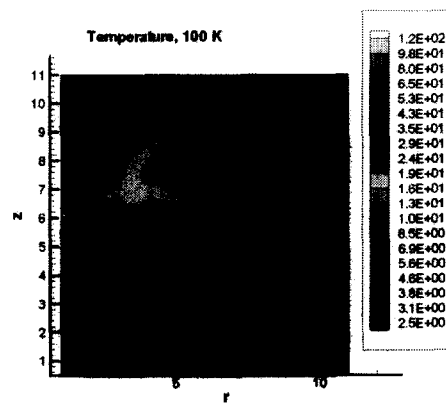
**Fig.3** Temperature distribution at the divergent plasma jet entering the incident gas, consumption of a gas 0.2 g/s, inflowing gas pressure 0.2 atm, plasma generator power 15 kW, time  $30 \cdot 10^{-4}$  s



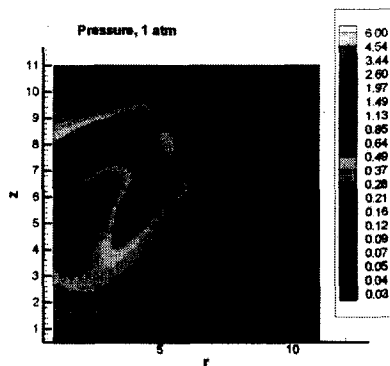
**Fig.4** Mach number distribution at the divergent plasma jet entering incident gas , consumption of a gas -0.2 g/s, inflowing gas pressure -0.2 atm, plasma generator power -15 kW, time - $30 \cdot 10^{-4}$  s



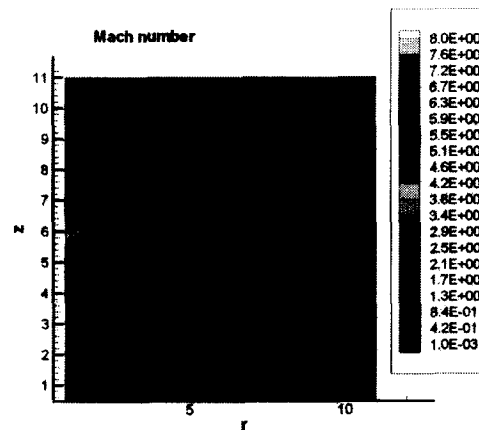
**Fig.5** Module of the velocity distribution at the divergent plasma jet entering the incident gas , consumption of a gas -0.2 g/s, inflowing gas pressure -0.2 atm, plasma generator power -15 kW, time -  $30 \cdot 10^{-4}$  s



**Fig.7** Jet interaction with the cross flow at ( $\theta=135^\circ$ ). Temperature distribution at the divergent plasma jet entering the incident gas, consumption of a gas is 0.2 g/s, inflowing gas pressure is 0.2 atm, plasma generator power is 15 kW, time is  $30 \cdot 10^{-4}$  s

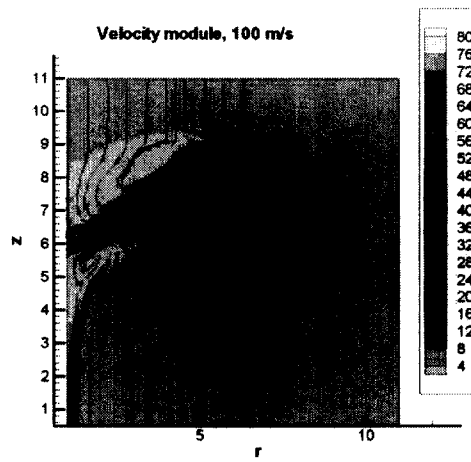


**Fig.6** Jet interaction with the cross flow at ( $\theta=135^\circ$ ). Pressure distribution at the divergent plasma jet entering the incident gas, consumption of a gas 0.2 g/s, inflowing gas pressure 0.2 atm, plasma generator power 15 kW, time  $30 \cdot 10^{-4}$  s



**Fig.8** Jet interaction with the cross flow at ( $\theta=135^\circ$ ). Mach number distribution at the divergent plasma jet entering the incident gas, consumption of a gas is 0.2 g/s, inflowing gas pressure is 0.2 atm, plasma generator power is 15 kW, time is  $30 \cdot 10^{-4}$  s





**Fig.9 Jet interaction with the cross flow at ( $\theta=135^\circ$ ).** Module of the velocity distribution at the divergent plasma jet entering the incident gas, consumption of a gas is 0.2 g/s, inflowing gas pressure is 0.2 atm, plasma generator power is 15 kW, time is  $30 \cdot 10^{-4}$  s