37. CROSSED SUPersonic jets of a plasma and a dense gas

Chernikov A.V., Chernikov V.A., Chuvashev S.N., Ershov A.P., Shibkov V.M.,
Timofeev B.I., Timofeev I.B.
(Moscow State University, 119899 Moscow, Russia)

Abstract. For an ignition of supersonic flows of air-fuel mixtures under the conditions characteristic for the ramjet engines, it is advantageous to inflame the internal regions of the flows rather than the peripheral zones. Usual electric igniters produce a plasma volume just nearby their electrodes. Any installation of a construction into the flow causes a significant drag. However, some types of discharges produce plasma jets that can penetrate deeply into the air-fuel mixture flows. The processes of generation of these jets by the capillary and plasmodynamic discharges, and the processes of interaction of the jets with transversal supersonic gas flows are considered experimentally and theoretically.

The capillary discharge was organized in a conic dielectric unit (4) which contained a couple of electrodes (Fig.1), which were separated for 3 mm. An organic glass spacer with a $\varnothing 1 \times 3$ mm cylindrical bore – the capillary – was fixed between the electrodes. The upper conic W-Cu electrode (1) had a $\varnothing 3 \times 15$ mm orifice. The lower graphite electrode (3) had a cylindrical shape, $\varnothing 10 \times 5$ mm.

Fig.1. The capillary design. 1,2- electrodes, 3- dielectric unit.

The plasmatron was operating with a power supply unit containing a 600 $\mu$F 1...2 kV capacitor battery, the pulse energy could be varied from 300 to 1200 J, the pulse duration was about $\tau = 1000 \mu$s.

A typical row of a high speed camera photo frames of the discharge appearance in a steady air is shown in Fig.2.

Fig.2. The capillary discharge in a steady air.

Fig.3 shows the temporary dependence of the plasma jet length. The rate of its growth $v_j$ is approximately in a direct proportion to the discharge input power. $v_j$ is higher in a rarefied air. The characteristic speeds of the plasma piston vary from supersonic ($\approx 450$ m/s at the air pressure $p = 20$ Torr) to subsonic ($\approx 300$ m/s at 80 Torr). The plasma flow speed inside the jet can be several times as high.

Fig.3. Temporary dependence of the capillary discharge plasma jet length.
Fig. 4 shows characteristic high speed camera photo frames of the capillary discharge appearance in a transversal supersonic airflow. The latter was organized by the atmospheric air injection into the 3 m³ vacuum chamber through the M=2 converging-diverging nozzle, the air jet thickness being about 2.5 cm. One can see that the plasma jet is bent by the airflow, the more, the lower is the input power. During the period of the highest electric power input, the plasma jet passes through all the air jet. In the beginning and in the end of the power supply pulse, the plasma jet does not penetrate into the airflow.

At higher initial pressure in the chamber (p=80 Torr), the plasma jet does not leave the airflow, but it fills a good deal of its cross section. The downstream plasma velocity is parallel to the airflow axis in this case.

The discharge processes in the capillary were analyzed with use of an assumption of a Π-shaped radial distributions of plasma density ρ, axial speed v, temperature T, pressure p. Steady distributions over the axial coordinate x (0 ≤ x ≤ X) were considered. Conductive and radiation heat transfer along x were neglected (the latter supposes low enough ∂T/∂x, that has proved to be true). Then the equations of radiating plasma dynamics [1] yield:

\[ \rho v \partial v/\partial x + \rho v \partial T/\partial x = m', \]
\[ \rho v \partial e/\partial x = -\gamma m' - \rho \partial p/\partial x, \]
\[ \rho v \partial e/\partial x = -p \partial e/\partial x + j/\sigma \]

(j is electric current density, σ is plasma conductance, m' is the erosive mass flow). The total current I, the channel’s sizes R,X, and the input power P corresponded to the experimental conditions; boundary conditions included \( v(x=0) = 0 \), \( M(x=X) = 1 \). One can deduce from (1) that \( m' = f' p/\rho \sigma \) at \( x = 0 \); there was assumed that \( \partial m'/\partial x = 0 \). The equations of state of the erosive plasma were taken from [2], the function \( \sigma = \sigma(T,\rho) \) took into account the effect of strong coupling [3].

Computations at \( P = 0.2...0.5 \) MW, \( I = 500...1000 \) A, \( L = 3 \) mm, \( 2R = 1...3 \) mm have shown that \( \partial T/\partial x \) is negligible, \( T = 1 \) eV, \( v = 2 \) km/s, \( p = 30...300 \) atm >> \( p_0 \) (\( p_0 \) is the static pressure of the gas flow). The values of \( \rho \) and \( p \) at \( x = X \) and the pressure head of the plasma jet depend greatly on \( R \), they fall for a decimal order of magnitude as the capillary diameter 2R grows from 1 to 3 mm. Note that it is very difficult to stabilize \( R \). Its relative growth due to erosion during the discharge time \( \tau \approx 1 \) ms

\[ \Delta R/R = p(x=X)v(x=X) R v/(2\rho_n XR) \]

(\( \rho_n \) is the density of the dielectric walls) achieves 0.3 for the modes characteristic for the current experiments.

The plasma jet formed by the capillary discharge is strongly under-expanded: \( n = p(x=X)/p_0 = 30...500 >> 1 \). In the current experimental set up, it exits the capillary and passes a 15 mm long \( \Omega 3 \) mm cylindrical metal channel. The jet’s acceleration and rarefaction in the channel is defined by the standard gas dynamical formulae for a diverging nozzle. The value \( n \) is still high at the channel’s nozzle. Outside the channel, the plasma flow is further broadened and accelerated, and the Mach disc is formed at a separation of \( l_m \), its diameter being \( d_M \); these values are given by semi-empirical formulae [4]:

\[ l_m = 1.4fr_n, d_M = g r_n, f = [n(1+\gamma)]^{1/2}, \]
\[ g = [1 + n(\gamma/2)^2(1 + 2/\gamma)]^{1/2} + [1 + n(1 + 2/\gamma)]^{1/2} - 1 + \gamma]^{1/2} \]

(\( \gamma \) is the adiabatic exponent). Calculations with the data from the capillary discharge model yield \( d_M \approx l_m \approx 1...2 \) cm. Such a jet still has a considerable pressure head.

The jet bends in the transversal gas flow, its central line form \( y = y(x) \) can be taken in accord with a semi-empirical relation [4]
\[ x = \frac{d_0}{K(y/d_0)^{2.55} + (y/d_0)(1+1/K)/\tan \alpha}, \]

here \( K \) is the ratio of the initial pressure heads of the plasma jet and the supersonic gas flow, \( d_0 \) is the initial jet diameter, \( \alpha \) is the initial angle between the flows.

The model agrees with experiments (Fig.5). Computations have shown that the plasma jet can penetrate deeply into the supersonic gas flow, it can pass all the width of the gas jet (see Fig.4). Note that the first experiments had shown a poor penetration of plasma into the gas flow; the first semi-period was 20\( \mu \)s long, the maximal discharge in the atmosphere are presented in Fig.6.

\[ \rho_l = 1.18kg/m^3, T_l = 12977K, p_l = 160atm, n=7.15, d_{le}r = 19.2mm, \Delta t_r = 18.2mm. \]

A plasma jet in a transversal gas flow is essentially 3D object, but to a first approximation it can be considered as a result of bending of an axially symmetrical jet. The latter under the conditions of the experiments (the Reynolds number \( Re = u \cdot L_*/v_0 = (3...5) \times 10^7 \) is laminar, though big vortices are formed (here \( v_0 \) is viscosity, \( L_*/v_0 \) is the characteristic length, \( v_0 \) is the characteristic speed). Distributions of plasma speed and temperature in the main region of a laminar jet are given by [5]
The plasmadynamic discharges are much shorter and far much brighter than the capillary discharges of the analogous pulse energy.

Typical temporary dependencies of the plasmadynamic discharge jet length in a steady air of different pressure are shown in Fig.7.

One can see that during the first semi-period (when the input power is high) the speed of the jet propagation is high enough ($v = 7.1 \text{ km/s at } p = 20 \text{ Torr}, v = 5.1 \text{ km/s at } p = 20 \text{ Torr}$), at the end of the discharge pulse current it falls to $v = 2.7 \text{ km/s at } p = 20 \text{ Torr}, v = 1.0 \text{ km/s at } p = 80 \text{ Torr}$. The higher is the pressure, or the less is the initial voltage, – the less is the speed of the jet propagation (the situation here is analogous to that for the capillary discharges).

Fig.7. Typical temporary dependencies of the plasmadynamic discharge jet length in a steady air of different pressure ($U_0=4\text{kV}$).

Fig.8 shows typical high speed camera frames of the plasmadynamic discharge in a transversal supersonic airflow. One can see that the plasma jet in the airflow is inclined relatively the axis of the discharge unit for an angle which is rather small and approximately constant during all the period of interaction. The plasma jet crosses all the airflow width during some 10...20 $\mu$s and exits at the same angle.

Fig.8. High speed camera frames of the plasmadynamic discharge in a transversal supersonic airflow.

In accord with experimental and theoretical studies [1-7], if the inter-electrode gap before the discharge is filled with a dense gas, the discharge passes through several stages: the surface discharge (like an arc), the discharge with a current sheath, the plasmadynamic discharge with a double cumulating, and the quasi-vacuum plasmadynamic discharge. The last stage is of the most interest for the purposes of formation of long plasma jets. It can be roughly considered as a combination of two independent complex processes: 1 – a formation of the plasma jet similar to that at the vacuum plasmadynamic discharge (i.e. in the case that the discharge gap is previously evacuated), 2 – the interaction of the hypersonic plasma jet with the dense gas.

The main processes at the vacuum plasmadynamic discharge are as follows [6-8]. Nearly a half of the discharge electric current flows near the surface of the dielectric insert. Plasma is formed of products of decomposition of the dielectric. The decomposition and further ionization and heating of the products is a result of absorption of a powerful radiation flux $S_0$ from the plasma focus PF in the radiation wave RW to be
formed near the surface. The plasma formed is accelerated by the Ampere force of the discharge current. Due to a considerable radial dependence of the length of the acceleration zone, the plasma flow is focused to the symmetry axis. As the flow is the length of the acceleration zone, the plasma flow accelerated by the Ampere force of the discharge formed near the surface. The plasma formed is rate is rather low. Actually, the major part of the shock wave SW. Note that the dielectric erosion here $M$ is the total mass is $M = M_j/\delta^2$, where $M_j$ is the density of the dielectric. E.g., at $E_j = 1$ kJ, $\rho_j = 2$ kg/m$^3$, $L = 0.5$ cm, $v_j = 50$ km/s, the total mass is $M_j = 0.8$ mg, and only $\delta = 5$ μm of the dielectric surface is gone. One should also take into account, that even a considerable erosion with $\delta < L$ does not alter significantly the discharge gap geometry and thus does not affect the main parameters of the discharge. This corresponds to $N = L/\delta = 1000$ discharges. Moreover, it looks possible to synchronize the processes of erosion of the electrodes and the dielectric so that the geometry of the inter-electrode gap would be the same at even more pulses (the electrode unit would be diminishing slowly, like a candle). In such a case, $N$ could be much higher than $L/\delta$. Thus, the plasmadynamic discharge units are very durable. It can be still improved, say, with use of a supply of a liquid or gaseous matter through pores in the dielectric insert and/or the electrodes (for the formation of the discharge plasma of this matter instead of the erosive mechanism of formation of the plasma of the dielectric material). The durability of the plasmadynamic discharges corresponds with the experimental practice.

To the first approximation, one can consider a one-dimensional interaction of the gas with a cylindrical hypersonic plasma jet, with a formation of two strong shock waves. If one considers the shock waves to be very strong, one can apply the following approximate expressions for the parameters of the shock structure:

$$v_j = v_{pl}[1+(\rho_j/\rho_{pl})^{1/2}],$$

$$p' = (\gamma_{pl} + 1)\rho_{pl} (v_j^2 - v_j^2)/2,$$

$$\rho_{pl} = G_{g} \rho_{pl}, G_{g} = (\gamma_{g} + 1)/\gamma_{g} - 1),$$

$$T_{pl}' = (\gamma_{pl} - 1) m_{pl} (v_j^2 - v_j^2)/(2k_B),$$

$$\rho_{g}' = \rho_{g}[G_{g} p'/p_{g} + 1]/(G_{g} + p'/p_{g}),$$

$$v_j = [(p'-p_{g})(V_{g} -V')^{1/2}, V' = 1/p',$$

$$D' = [(p'-p_{g})(1/\rho_{g}-1/\rho_j)^{1/2}/\rho_{pl}$$

$$T_{g}' = m_{pl} p'/p_{g}, x_j = \int v_j dt,$$

here $v_j$ is the speed of jet propagation, $p'$ is the pressure between the shock waves, $\gamma_{pl}, \gamma_{g}$ are the adiabatic exponents of plasma and gas, $\rho_{pl}, \rho_{g}$, and $T_{pl}', T_{g}'$ are the densities and temperatures of the compressed plasma and gas, $D'$ is the speed of the shock wave in the gas, $k_B$ is the Boltzmann constant, $m_j$ is the mean molecular mass of the compressed gas, $x_j$ is the axial size of the plasma jet. The speed $v_{pl}$ and density $\rho_{pl}$ of the plasma flow can be calculated with use of the model of the vacuum plasmadynamic discharge. This simplified approach results in a good correspondence with experimental data on the jet’s length, speed, etc.

![Fig.9](image)

**Fig.9.** Characteristic length of the plasma jet over the initial voltage and the electrode unit characteristic size at the gas density $\rho_{g} = 0.26$ kg/m$^3$

The calculations have been produced for a broad range of all the parameters. Computations in terms of parameters of a capacitor-based power supply source show that a very deep (up to 0.5 m) penetration is available with use of a capacitor battery with moderate parameters (see Fig.9). The plasma temperature $T_{pl}' = 3...30$ eV is far much higher than that needed for the ignition (1500...3500 K). The main mechanism of energy transfer between the plasma jet and the gas is the turbulent heat conductance. It means that a continuous temperature profile ranging from $T_{pl}'$ to $T_{g}' = 200...300$ K is formed, and there surely exists a region in the gas with the parameters optimal for the ignition.

Thus, an effective ignition of supersonic air-fuel mixtures can be provided far from the walls with use of a reliable, durable, low energy, small-size device on base of the plasmadynamic discharge.
References


