Hypersonic plasma flows created by a pulse capillary discharge

A S Pashchina
Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, Russia
fgrach@mail.ru

Abstract. The possibility of producing by a pulsed capillary discharge the quasi-stationary high-speed plasma flows in a wide range of Mach numbers (M=3-20), electron number densities (n_e〜10^{11}-10^{15} cm^{-3}) and temperatures (T_e〜3-10 eV), rotational and vibrational temperatures (T_r =3800-6000 K and T_v =9000-15000 K), which can be used for setting up plasma aerodynamic experiments on small laboratory facilities, is shown. The most suitable for this purpose is a mode close to supersonic outflow into a vacuum, the transition to which occurs when the total pressure ratio exceeds N = p_0/p_∞ > 5\cdot 10^4. This mode permits to obtain wide-aperture flows (D > 10 cm) with spatially extended weakly inhomogeneous segments sufficient to accommodate tested bodies of a centimeter scale.

1. Introduction

The creation of hypersonic aircraft (HA) is directly related to the solution of a number of scientific, technical and technological problems, involving experimental studies in conditions close to the real flight of HA. The complexity and high cost of full-scale experiments [1], as well as studies on large-scale test benches [2,3], makes it relevant to search for ways to produce high-speed flows in small laboratory installations, allowing one to solve quickly individual tasks with less stringent requirements for the validity of similarity criteria and flow parameters. In many cases, laboratory experiments are an acceptable alternative to costly bench and flight experiments and, unlike the latter, have important advantages, including efficiency of obtaining the result, as well as more wide options for choosing the diagnostics methods and tools. At the same time, it is highly desirable to be able to produce the flows, whose parameters are close to the real conditions of hypersonic flight, namely: the stagnation enthalpy - h^* > 20 MJ/kg, the stagnation pressure - p^*〜10^4-10^5 Pa, the Mach number of incident flow - M > 6. Such parameters are easily achieved in plasma flows created by a pulsed discharge in a capillary with an evaporating wall. As was shown previously [4,5], this method allows one to produce in an rarefied gas atmosphere the quasi-stationary high-speed plasma flows with a duration of t = 1-100 ms in a wide range of Mach numbers M = 3-20, gas temperatures T = 3000-6000 K and charged particles densities n_e = 10^{11}-10^{15} cm^{-3}, that creates wide opportunities for setting up the plasma-aerodynamic experiments. The undoubted advantage of capillary discharge is the ability to select the type and method of supplying the plasma-forming substance that allows one to simulate the conditions of hypersonic flight in the atmospheres with different chemical composition.

The most important requirement for an aerodynamic experiment is to ensure the spatial homogeneity of the flow parameters on the scales exceeding the dimensions of the tested bodies. This requirement can be satisfied simply enough for stationary flows with fully controlled parameters, for
example, by installing special supersonic nozzle \( (p_e = p_\infty, \ p_e - \text{pressure at the nozzle exit, } p_\infty - \text{ambient pressure}) \) providing design flow condition. This solution is hardly suitable for pulsed flows with time-varying parameters. In the latter case, a suitable solution is to place the tested bodies in those flow segments, where the flow parameters changes rather slowly. For highly underexpanded supersonic jets, such a segment is located inside a single section of the shock-wave structure that forms in the initial part of the jet. The length of the weakly inhomogeneous segment, as well as the dimensions of the shock-wave section, is determined by the total pressure ratio \( N = p_0/p_\infty \) (\( p_0, p_\infty - \text{pressure inside the capillary and in ambient atmosphere, respectively} \)). It can be expected that for the large values of total pressure ratio \( N > 10^3 \), the dimensions of the weakly inhomogeneous section will be sufficient to accommodate tested bodies of a centimeter scale. Determining the conditions for obtaining, as well as studying the structure of such flows was one of the objectives of this work.

Another task of the work was to select the appropriate diagnostic methods and to determine the basic electrophysical, gas-dynamic, and thermophysical characteristics of pulsed plasma flows injected into a rarefied atmosphere. This paper focused on the experimental determination of flow parameters such as the Mach number, electron density and temperature, and the temperature of the heavy component. For this purpose, a set of independent diagnostic methods is examined: quantitative spectroscopy, probe diagnostics, visualization of supersonic flows based on gas-discharge and shadow methods.

2. Experimental facility
Principal design of the experimental facility is presented in figure 1. The capillary arrester, whose detailed description is given elsewhere [6], is used for the plasma jet producing. Polymethylmethacrylate (PMMA) is used for capillary fabrication, whose chemical formula \( \text{C}_3\text{H}_5\text{O}_2 \) determines the initial stoichiometric composition of the plasma. The discharge power source is the energy storage device consisting of a capacitor banks connected to the discharge circuit through a time-delaying inductance. The discharge power source provides following parameters: the storage energy \( Q = 90-640 \text{ J} \), the amplitude of the discharge current \( I_m = 100-2500 \text{ A} \), and the duration discharge pulse \( \tau_d = 2-20 \text{ ms} \). The mass-average enthalpy of the obtained plasma at the specified parameters of the discharge power source is \( h = 100-200 \text{ MJ/kg} \). The arrester is placed in a vacuum chamber, the ultimate vacuum is \( p = 13 \, \text{ Pa} \). The vacuum chamber is equipped with quartz windows, which makes it possible to diagnose the discharge using shadow and spectral methods. Tested bodies of various shape (such as a sphere, a cone, an asymmetrical wedge, a thin plate etc.) were placed in the center of vacuum chamber along the axis of the capillary. The main part of experiments were carried out in an air atmosphere in the pressure range of \( p_\infty = 13-10^5 \, \text{ Pa} \). In some cases we used argon and helium as tested gases.

To study the flow pattern, we use the registration of the own and shadow images of the selected jet segment using a MotionPro N3 high-speed video camera (exposure duration - 1 \( \mu \text{ s} \), frame rate - up to 10 kHz). The emission spectra of the plasma in the wavelength range 280-800 nm were recorded using an AvaSpec UL-2048 spectrometer. The recorded emission spectra were used to estimate the component composition and the main parameters of the plasma — the number density of charged particles, vibrational and rotational temperatures. Also, the Langmuir triple probe method is used to determine the electron number density and temperature [5].

3. Experimental results
One feature of capillary discharge plasma injected into the rarefied atmosphere is a low value of the effective adiabatic index tending to unity \( \gamma \rightarrow 1 \) [4], that is a sign of significant concentrations of polyatomic molecules and condensed particles. The sources of condensed particles are the ablation products of the carbon-containing capillary wall and the electrodes substance. The formation of condensed particles is possible in a limited temperature range \( T = 1500-5000 \, \text{ K} \) [7,8], which, according to the results of spectral diagnostics (see below), are achieved in a plasma jet injected into a rarefied atmosphere. This result is quite expected, since the production of condensed particles was observed
earlier for plasma jets injected into a gas at atmospheric pressure [9]. Estimates based on the results of the extinction measurements show that the characteristic size of condensed particles is 2–4 nm, the cluster formation time is 0.2–0.4 µs, and their concentration is $10^{13}$ cm$^{-3}$. These estimates are consistent with the results of measurements of the condensed particles parameters by scanning electron microscopy [9].

One of the objectives of the research was to study the conditions for obtaining hypersonic flows with homogeneous segments, the length of which is sufficient to accommodate centimeter-scale tested bodies. For this purpose, a pattern of the flow around a thin plate with a pointed front edge placed at various distances from the capillary outlet was studied. The Mach number of the flow was determined by the inclination angle of the attached shock wave. Two parameters were varied during the research - the distance between the plate edge and the capillary outlet ($z = 5$-100 mm) and the total pressure ratio ($N = p_0/p_\infty = 2-3 \times 10^3$). The total pressure ratio was set by an appropriate choice of pressure in the vacuum chamber ($p_\infty = 13 \times 10^3$ Pa) and/or pressure inside the capillary ($p_0 = 0.2$-4 MPa). The value of the last one is determined by the power of the discharge pulse and capillary sizes.

We can distinguish two typical flow modes of a supersonic jet, depending on the total pressure ratio: the mode with the formation of a shock-wave section in the initial part of the jet and the mode close to supersonic outflow into a vacuum. The formation of a shock-wave section is observed up to the total pressure ratios of $N \sim 10^3$. In this mode, one of the main elements of the shock-wave structure is clearly observed - the central shock wave (Mach disk), which significantly distorts the pattern of the flow around a thin plate, interacting with the attached shock wave (figure 2(a)). The shock wave structure does not form if the total pressure ratio exceed $N > 5\times 10^3$. In this case, the classical pattern of
supersonic flow around a thin plate with the formation of the attached shock wave (figure 2(b)) is observed, and this mode turns out to be close to supersonic outflow into a vacuum.

![Image](supersonic_flow.png)

**Figure 2.** The influence of the total pressure ratio $N=p_0/p_\infty$ on the flow mode of a plasma jet and the pattern of the flow around a thin plate: (a) the mode with the formation of the shock-wave structure ($N\approx100$), (b) the mode close to supersonic outflow into a vacuum ($N\approx7\cdot10^3$), (1) central shock wave (the Mach disc), (2) attached shock wave.

The flow structure in this mode is characterized by the presence of an expansion section, along which the flow accelerates (figure 3), and a stationary section, at which the jet diameter and the Mach number vary slightly. The expansion section length $L$, as well as the transverse size of the jet $D$ on the stationary section, varies in proportion to the square root of the total pressure ratio, i.e. $L \sim \frac{D}{d} \sim \sqrt{N} = \sqrt{\frac{p_0}{p_\infty}}$ ($d$ – diameter of capillary). Thus, when pressure inside the capillary is $p_0 = 1$ MPa, and the pressure in the vacuum chamber is $p_\infty \approx 130$ Pa, the length of the expansion section is approximately $L \approx 2$ cm, and the transverse dimension of the jet stationary section exceeds $D > 10$ cm. The Mach number at a considerable length of the stationary section varies slightly. For the above mentioned
parameters, the length of such segment reaches 8-10 cm at the characteristic values of Mach number of $M \sim 15-20$.

The emission spectrum of a plasma jet (figure 4) is represented by the intense molecular spectra of the Swan band system of C$_2$ radical (the bands $\Delta \nu = -1, 0, +1$, +2 of $d^3\Pi_g - a^3\Pi_u$ transition), the violet band system of CN radical (the bands $\Delta \nu = 0, \Delta \nu = -1$ and $\Delta \nu = 1$ of $B^2\Sigma^+ - B^2\Sigma$ transition), and also by weak H$_a$ and H$_g$ lines of the Balmer hydrogen series. Lowering the vacuum chamber pressure below $p_{\infty} < 10$ Torr leads to the appearance of molecular bands of CH, N$_2$, NO, CO, O$_2$ radicals that indicates lowering of the gas temperature – at least below 5000 K. The simultaneous presence in the spectra of the Balmer hydrogen lines and molecular bands indicates high values of the electron temperature (not less than $T_e > 1$ eV) and a significant deviation of the plasma from thermodynamic equilibrium. The latter factor limits the possibility of using the standard methods of quantitative spectroscopy to determine the electron temperature, as well as vibrational and rotational temperatures. In particular, the violation of the Boltzmann equilibrium leads to a variation in the values of the vibrational and rotational temperatures, determined by different sequences of the molecular bands of the C$_2$ radical. The vibrational and rotational temperatures determined in this way are enclosed in the ranges $T_v = 9000$-$15000$ K and $T_r = 3800$-$6000$ K.

Based on the obtained spectra, we estimated the vibrational and rotational temperatures in the regions ahead and behind the shock wave. According to these estimates, higher temperatures correspond to the region behind the shock wave. Based on these data, the estimates of the Mach number ahead the shock wave were made, which are consistent with the results obtained by analyzing the shock-wave structures formed in the vicinity of the streamlined bodies.

![Figure 4](image_url)

**Figure 4.** Emission spectrum of a plasma jet. The ambient gas is air, the pressure in the vacuum chamber is $p_{\infty} = 400$ Pa, the total pressure ratio is $N \sim 3 \times 10^3$.

More suitable methods for non-equilibrium plasma diagnostics are the electric-probe methods, whose advantages are the “insensitivity” to the plasma thermodynamic state and the possibility of local measurements. In this work, we used the triple Langmuir probe method [5], which provides the possibility of simultaneous and continuous measurement of the electron number density and temperature during a discharge pulse. Measurements were performed for a jet flow mode close to supersonic outflow into a vacuum ($N > 5 \times 10^4$). The probe was placed in the axial zone of the flow at different distances from the capillary outlet - $z = 5$-$10$ cm. It was found that, at $N > 10^4$, the electron number density and temperature in this section of the flow change only slightly (no more than 10–15%), that further confirms the possibility of obtaining hypersonic flows with spatially extended
slightly non-uniform segments sufficient to accommodate centimeter-scale tested bodies. The electron number density depends significantly on the discharge power. Thus, increasing the discharge power by two orders of magnitude (from $P = 1$ kW to $P = 100$ kW) leads to a change in the electron number density by three to four orders of magnitude – from $n_e = 10^{11}$-10$^{12}$ cm$^{-3}$ to $n_e = 10^{14}$-10$^{15}$ cm$^{-3}$ (figure 5(a)). In this case, the electron temperature changes in the range of $T_e = 3$-10 eV and decreases as the discharge power increases (figure 5(b)).

Figure 5. Time dependences of (a) the electron number density and (b) temperature on the weakly nonuniform segment of hypersonic flow, obtained by triple Langmuir probe method for various discharge power. The values of discharge power $P$ are indicated in the plots legend. The probe is placed in the axial flow zone at the distance of $z = 10$ cm from the capillary outlet. The pressure in the vacuum chamber is $p_\infty = 130$ Pa, the total pressure ratio is $N \approx 7 \cdot 10^3$.

4. Conclusions
The possibility of producing by a pulsed capillary discharge the high-enthalpy hypersonic gas-plasma flows in a wide range of Mach numbers ($M = 3$-20), electron number densities ($n_e \sim 10^{11}$-10$^{15}$ cm$^{-3}$) and temperatures ($T_e \sim 3$-10 eV), rotational and vibrational temperatures ($T_r = 3800$-6000 K and $T_v = 9000$-15000 K), is shown. Characteristic features of plasma flows injected into a rarefied atmosphere are the strong temperature non-equilibrium ($T_e/T_g > 10$), as well as low values of the effective adiabatic index ($\gamma \to 1$), indicating intense precipitation of the condensed phase (polyatomic molecules and nanoscale particles). The most suitable for conducting the plasma aerodynamic experiments is the flow mode close to supersonic outflow into a vacuum, the transition to which occurs when the total pressure ratio exceeds $N = p_0/p_\infty > 5 \cdot 10^3$. This mode permits to obtain wide-aperture flows ($D > 10$ cm) with spatially extended weakly inhomogeneous sections sufficient to accommodate tested bodies of a centimeter scale. An important step in future research should be the preparation and approbation of the quadruple Langmuir probe method [10], which will expand the set of measured parameters by including such important parameter as the plasma flow velocity.

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