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► To cite this version:

Pascal Tardy, Michel Dudeck. Magnetohydrodynamic velocimetry of a low-pressure plasma jet.. Review of Scientific Instruments, 1992, 63 (8), pp.3985. 10.1063/1.1143250 . hal-00404218

HAL Id: hal-00404218

<https://hal.science/hal-00404218v1>

Submitted on 16 Jul 2009

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Magnetohydrodynamic velocimetry of a low-pressure plasma jet

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The velocity of a steady, low-pressure (~ 0.1 Torr) plasma jet is measured by analyzing the local response of the medium to the action of an external magnetic field set up by two Helmholtz coils placed at the edge of the jet, yielding a field of 0.92 G/A. The induced electric field is measured by two floating-potential electrostatic probes. The mean velocity of the electrons (between 1000 and 5000 m/s) is found from the generalized Ohm's law.

I. INTRODUCTION

There are several important reasons to measure the velocity of a gas flow: to determine the subsonic or super-sonic character of the flow, to evaluate a mechanical time that can be compared with the characteristic relaxation times of the various chemical and thermal phenomena active in the jet, or to initialize some computer codes in which the convective effects are simulated.

Various techniques are usually employed for determining the velocity of an ionized gas (plasma) flow. Laser-Doppler anemometry, for example, provides a local measurement of the velocity of solid particles injected in the flow. This can be used on plasma jets at atmospheric pressure [1], but not at low pressure since the particles do not then fly at the same velocity as the jet.

In the time-of-flight method, the time of propagation of a disturbance between two points is measured. This method yields only a mean velocity. But there are many ways of applying it. Cabannes et al. [2] for example, performed an optical analysis of a sinusoidal disturbance of the arc current. Hoell et al. [3] used a current pulse generator and a double-probe system. Yoshikawa et al. [4] disturbed the flow with a high-capacitance device. Cason [5] and Girard et al. [6] introduced an excess of ions in the jet with an electron-gun, and Gaucherel and Rowe [7] seed the jet with special ionic species, and they both then measure the ion time-of-flight by mass spectrometry. Kay [8] used a notched wheel to chop the jet, and a mass spectrometer to get the velocity. Cambray [9] used two photodiodes to determine the time-of-flight of a natural fluctuation of the plasma.

The flow velocity of a plasma can be given by analyzing the ionic current collected by a pair of cylindrical electric probes inclined with respect to the flow velocity vector and perpendicular one to each other. Several theories [10-12] describe the relation between the ionic currents of the two probes. This method is used by Clayden [10] and Levin and Khmelinin [13], to determine the velocity of the ions. Poissant and Dudeck [14] used it for argon jets, as Segall and Koopman [15] did. The precision of this method is poor at subsonic velocities. For supersonic jets, the shock effect and a probe wake effect disturb the velocity field and this method becomes unreliable and tricky to use. Furthermore, it only yields the ion velocity dedimensionalized by the most probable velocity of the ions, so the ion agitation temperature has to be known in order to determine the ionic velocity.

The flow velocity can also be determined by measuring the Doppler shift of a spectral line. Cambray [16] uses this approach to find the velocity of a helium plasma low-pressure jet while Levin and Khmelinin [13] use it on an argon jet, and Kroesen [17] to measure the velocity of argon atoms and the CH radical. This technique requires a high-resolution interferometer.

The CNRS Aerothermics laboratory is studying high-temperature, low-pressure ionized gas flows to stimulate high-velocity spacecraft atmospheric reentry. These plasma jets are generated by arc heaters. The velocity measurement method described in the present paper uses the response of the plasma to the action of an external magnetic field. Generalized Ohm's law is applied to find the flow velocity from the electric field, measured by double floating electrostatic probes.

II. EXPERIMENT

The experimental setup [18] generates steady plasma jets at low pressure and high temperature, in a cylindrical test chamber 1 m in diameter and 2.35 m long (Fig. 1). These jets are created by blown electric arc generators with regulated currents between 0 and 500 A. An arc is generated between a needle point of tungsten alloy (2% thorium) and the throat of a copper nozzle. This arc heats, ionizes, and eventually dissociates, a gaseous flow injected with a vortex motion around the cathode. The arc is initiated by high-voltage, high-frequency (4 kV, 1 MHz) discharge between the electrodes, which are 4 mm apart.

Three gases are used: nitrogen, argon, and hydrogen. The arc current is 100 A and the flow rate is 15 standard litres per minute. The static pressure in the chamber and outside the jet is respectively 0.15, 0.20, and 0.12 Torr. The resulting ionized jet expands in the chamber, where the vacuum is held by a vacuum unit operating at a rate of 20 000 m³/h at 5×10^2 Torr. The jet dimensions are large, e.g., 0.50 m in diameter and 1 m long, their electron density is between 10^{10} and 10^{11} cm⁻³ and the electron temperature ranges between 2000 and 8000 K. Electron temperature T_e and electron density are determined with Langmuir probes assuming a Maxwellian energy distribution for electrons and a collisionless potential sheath. In nitrogen, the temperature T_h of heavy particles is measured by optical spectrometry assuming equality between translation

and rotation temperatures. In this gas, T_h and T , are found to be of the same order of magnitude. This condition is assumed to be verified in the other gases.

III. GENERALIZED OHM'S LAW

The generalized Ohm's law, which is the basic equation used for measuring velocity by magnetohydrodynamic effect, relates the magnetic field applied to a given ionized medium, to the electric field induced in it. Various formulations of this law exist in the literature (see Delcroix [19], Sutton and Sherman [20] and Davies [21]). These three approaches, which use the species momentum equations, have several assumptions in common: three types of particles are considered (atom or neutral molecule, electron and molecular or atomic ion), the plasma is assumed to be electrically neutral, the electrical conductivity is scalar, and there are no viscous effects. Furthermore Delcroix [19] assumes quasi-isotropic medium, which comes down to neglect the convection terms; and using only the electron and ion momentum equations, he gets for the total current:

$$\mathbf{J} = \sigma \left(\mathbf{E} + \mathbf{v}_e \times \mathbf{B} - \frac{\nabla p_e}{n_e q_e} \right)$$

where σ is the gas conductivity, \mathbf{v}_e , is the mean electron velocity, and p_e the electron pressure.

$$\sigma = \frac{n_e q_e^2}{m_e (\nu_{ei} + \nu_{en})}$$

In Sutton and Sherman's approach [20], the time variation of the diffusion velocity is neglected compared with the time variation of the mean mass velocity. In the electron momentum where the inertia term is neglected, the ionic current is eliminated using the ion and the overall momentum equations. Assuming that the electrons and neutrals are in quasi-thermal equilibrium, and that the ion-neutral collision frequency is not much different from the electron-neutral collision frequency,

$$\mathbf{J} = \sigma \left(\mathbf{E} + \mathbf{v}_e \times \mathbf{B} - \frac{\nabla p_e}{n_e q_e} - \frac{1}{n_i m_i \nu_{in}^*} [-\nabla p_e \times \mathbf{B} + \mathbf{B} \times (\mathbf{J} \times \mathbf{B})] \right)$$

In this expression, the first two terms give the effect of the electromagnetic forces, while the third accounts for electron pressure gradient and the fourth (ion slip) results from the difference of velocity between the ions and neutral particles, to the magnetic field. ν_{in}^* , is related to the ion- neutral collision frequency ν_{in} ,

$$\nu_{in}^* = m_n \nu_{in} / (m_i + m_n) .$$

In the Davies formulation [21], the plasma is considered to be standard and the difference between the ion and electron convection terms is negligible compared with the $\mathbf{J} \times \mathbf{B}$ term, which is true if the mean variations of the ion and electron longitudinal velocities are much smaller than the cyclotron frequency of the electrons. For the jets considered, this frequency is about 10^7 s^{-1} , while the longitudinal variation in the velocity along the jet never exceeds $5 \times 10^3 \text{ s}^{-1}$. This assumption is therefore quite reasonable.

By subtracting electron momentum equation from ions momentum equation, assuming that the electron density is low compared with that of the neutrals, and adopting the same assumption as before for the collision frequencies, Davies obtains Ohm's law in the form:

$$\mathbf{J} = \sigma \left(\mathbf{E} + \mathbf{v}_e \times \mathbf{B} - \frac{\nabla p_e}{n_e q_e} \right)$$

Considering the experimental characteristics of the plasma wind tunnel, the Sutton and Sherman approach is selected, the nonsteady terms characterizing plasma instabilities can be eliminated by the mean of the overall momentum. In this equation, the first term relating to the electron pressure gradient can be neglected (evaluated as a function of temperature and electron density, this term is about 10^{-1} V/m while the $\mathbf{v}_e \times \mathbf{B}$ term is of the order of unity for a magnetic field of the order of 10^{-3} T). The second term involving the electron pressure gradient is also neglected (about 10^{-5} V/m , with $\mathbf{v}_e = 10^3 \text{ m/s}$, $n_i = 10^{18} \text{ m}^{-3}$, $m = 10^{-16} \text{ kg}$ and $\nu_{in}^* \sim 10^{18} \text{ s}^{-1}$). The last term of the equation represents the ion slip effect, it can be neglected if the Hall

parameter: $\omega_e \omega_i / \nu_e \nu_{in}^*$ is much less than unity, where ω_e , and ω_i are the cyclotron frequencies of the electrons and ions, respectively. In our experimental conditions, this quantity ranges between 10^{-3} for argon and 10^{-2} for hydrogen. With these orders of magnitude, Ohm's law takes a simple form that will be used to determine the electron flow velocity:

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{v}_e \times \mathbf{B})$$

IV. EXPERIMENTAL SETUP

The magnetic field is created by two Helmholtz coils, each consisting of 17 loops of copper tubing (outer diameter 5 mm). Each coil loop is wrapped with fiber glass impregnated with heat resistant resin, to insulate it both thermally and electrically, and water is circulating through the tubing to cool it. The outer diameter of each coil is 4.0 cm and the inner diameter 30 cm. The two coils are separated by a distance of 35 cm. The magnetic field created at the center of the coils is 0.92 G/A.

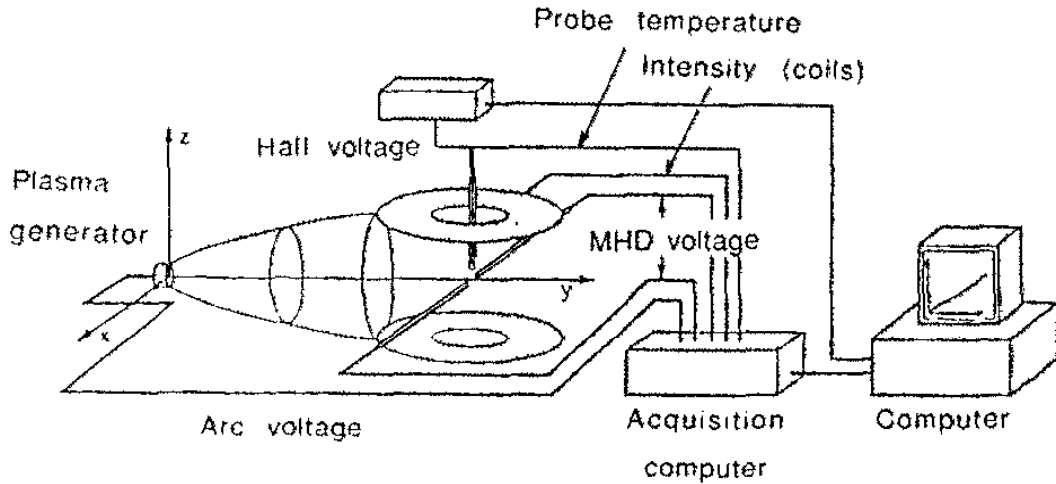


FIG. 1. Experimental device used for velocity measurements.

The magnetic field at the center of the coils is monitored by a Hall-effect probe placed in one of the branches of a water-cooled U-shaped copper tube and its temperature is controlled by a thermocouple. The induced electric field is determined by two floating-potential electric probes. Each probe consists of a tungsten rod 2 mm in diameter, inserted in an alumina tube. The sensitive part of the probe is its flat end, which comes into contact with the plasma. The ends of the two probes are placed 1.1 cm apart. For each probe, the difference between the plasma potential and the floating potential depends only on the electron density and temperature. As the electron characteristics of the measurement area are uniform [22], this difference is the same for both probes. The curve relating the magnetic field to the difference of potential between the probes is obtained by varying the coil current at a frequency of 0.01 Hz. The nonsteady effect of the magnetic field is negligible because the period of the collisions in the plasma, which is of the order of 10^{-8} s, is very much less than the 100 s period of the coil current.

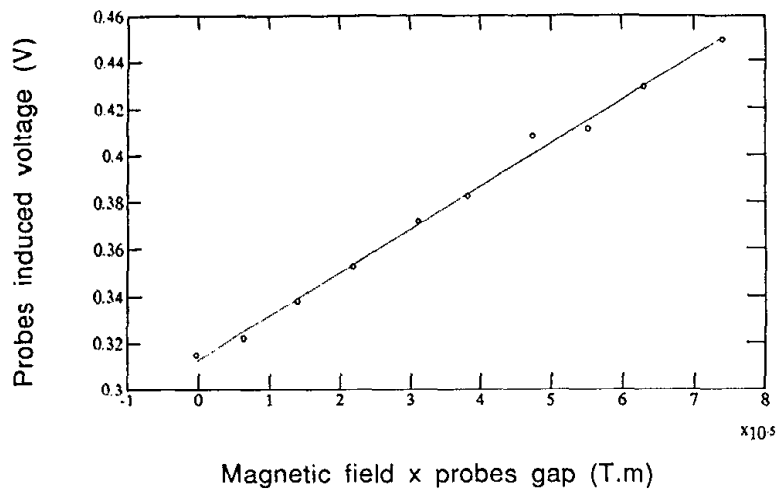


FIG. 2. Fit of experimental data in an argon jet.

The various parameters-generator arc voltage, voltage between the electrostatic probes, and current flowing in the coils-are recorded by an Orion acquisition computer. The device samples the various parameters,

making up a measurement point. The electron velocity of the plasma is determined by a computer code that searches the best optimization of Ohm's law. Ten points $E(B, v)$ are sampled during one period of the magnetic field (-100 s). These points generate an $E(B, v)$ characteristic which is numerically fitted by a straight line in a least-squares sense (Fig. 2). The jet velocity is then equal to the slope of this line.

V. RESULTS

Figure 3 shows the axial velocity distribution of an argon jet along the longitudinal flow axis for two series of measurements.

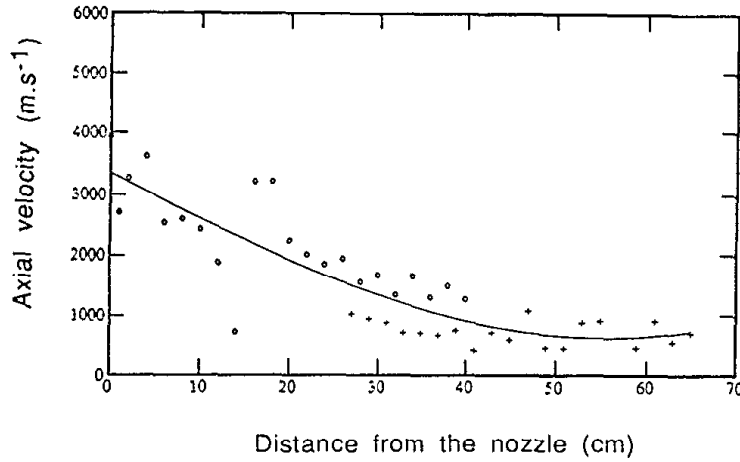


FIG. 3. Axial velocity in an argon jet.

The radial distribution of the velocity (Fig. 4) about the jet axis exhibits an increase in velocity starting at 60 mm. This effect, which has already been observed in jets subjected to magnetic fields [13][22], could be explained by the electron diffusion at the edge of the jet, or by the non-uniformity of the magnetic field in this area, which introduces eddy currents.

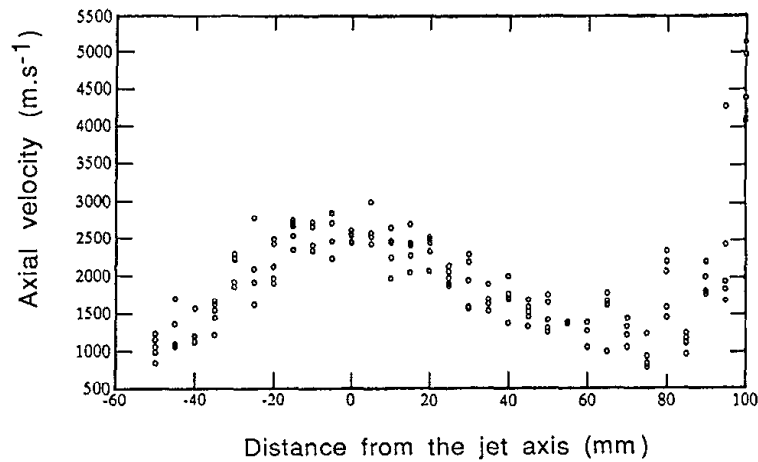


FIG. 4. Radial profile of the axial velocity in an argon jet.

The same distribution was recorded with nitrogen jets (Fig. 5). The velocities of nitrogen and argon jets, in the same experimental conditions, are of the same order, which is not the case for hydrogen jets (Fig. 6).

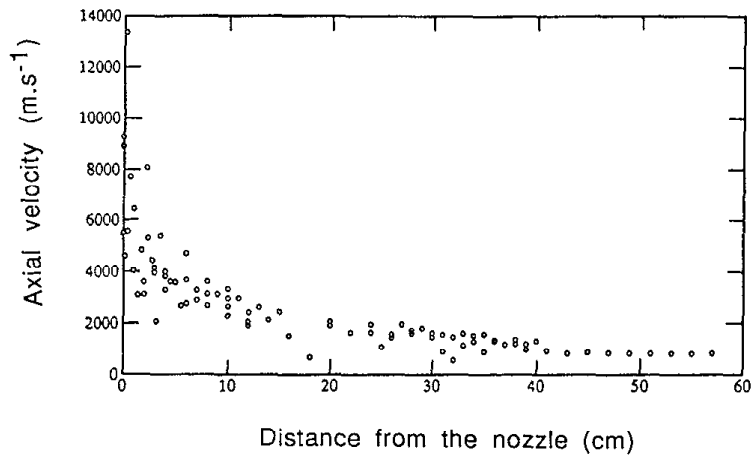


FIG. 5. Axial velocity in a nitrogen jet,

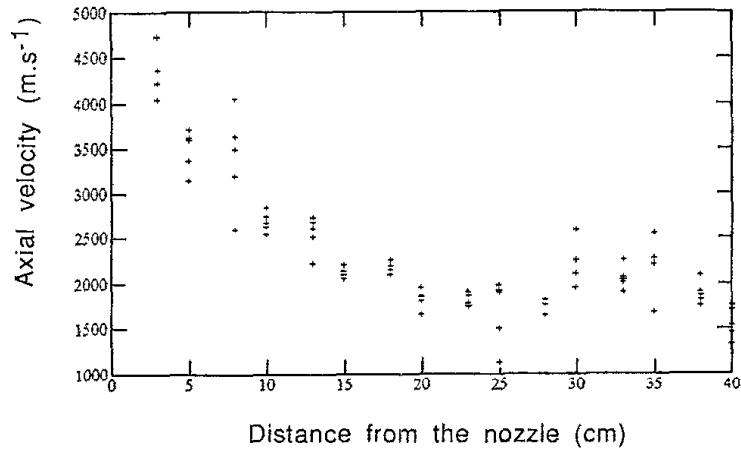


FIG. 6. Radial profile of the axial velocity in an hydrogen jet.

This is in conformity with the results of Malliaris [23]. The differences observed in the results at the same point in the plasma jet and for the same gas are due to the fluctuations in the arc creating the plasma. The distance between the probes was changed, to evaluate its effect on the measurement: a variation of this distance from 9.5 to 20 mm revealed no evidence of any significant variation. It was also verified that the magnetic field set by the coils does not modify the electron density and the electron temperature of the plasma jet. The electron temperature and density were measured by an electrostatic probe supplied at a frequency of 100 Hz. These parameters were determined using one of the probes employed for the velocity measurement, with a magnetic field ranging between 0 and 36.8×10^{-4} T (maximum current of 40 A flowing in the coils). No significant variation was observed in T_e (≈ 3000 K), or n_e ($\approx 10^{18} \text{ m}^{-3}$), which is in agreement with Chen [24]. Tests carried out with currents of 50-250 A showed that variations in the arc current have a negligible effect on the jet velocity: the essential part of the kinetic energy comes from the expansion of the gas in the plasma generator nozzle.

VI. DISCUSSION

The method presented provides a way of measuring the macroscopic flow velocity of electrons. This velocity is equal to the center of mass velocity if the diffusive effects are negligible, which is mainly the case in the vicinity of the jet axis. The spatial resolution depends on the separation between the probes used to measure the electric field (control volume for our experiment: 0.3 cm^3). The value obtained for the velocity agrees with those determined by a time-of-flight method using the natural fluctuations of the floating potential of the plasma (potential corresponding to a null current collected by an electrostatic probe).

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