# Experimental Study of Velocities in a Free Jet in a Rarefied Atmosphere

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**The jets studied by the authors are nitrogen free jets obtained with a sonic nozzle of throat diameter $d=2.10^{-3}$m. The stagnation temperature $T_0$ is generally equal to the ambient temperature $T_c=293$ K; the stagnation pressure ranges from 0.07 bar to 1 bar. The chamber $P_c$ ranges from $5.10^{-3}$ Torr to $10^{-1}$ Torr. The method used is based on the "ion time of flight" technique. The large dimensions of the wind tunnel enabled examination not only of the barrel shock but also of the wake downstream a considerable distance from the Mach disk (3 to 4 times the distance from the nozzle throat to the Mach disk). The wake downstream from the Mach disk is an important, complex zone where diffusion, mixing and even relaxation phenomena interact.**

## Introduction

OPTICAL methods are very often used for velocity measurements in rarefield gases essentially because they avoid disturbing the flow. A method based on the Doppler effect has been used by Muntz[1]; velocity $u$ is given in terms of the velocity of light $c$ by the relation

$$(u/c=-(\Delta\lambda/\lambda)$$

where $\Delta\lambda$ represents the spectrum line (of wavelength $\lambda$) enlargement by Doppler effect.

Currently, Muntz has only managed to use this method for helium, which exhibits a highly visible spectrum line, the enlargement of which is quite substantial (the 5015. 65 Å line). Cattolica[2] applied this method on a free jet axis and proceeded to study the instability of translational degrees of freedom. Muntz[3] by perpendicular and parallel measurements at the jet axis, confirmed Hamel and Willis' theory which used an ellipsoidal collision model, in the hypersonic regime, where the distribution function is not Maxwellian but is given by

$$f'=n'\left[\frac{m}{2\pi kT_\perp}\right]^{1/2}\exp\left[-\frac{mV^2}{2kT_\perp}\right]$$

$$+n'\left[\frac{m}{2\pi kT_{//}}\right]^{1/2}\exp\left[-\frac{m(v_{//}-v)^2}{2kT_{//}}\right]$$

$T_\perp$ and $T_{//}$ being "perpendicular" and "parallel" temperatures, respectively.

Bütefisch and Venneman,[4] finding it impossible to apply the Doppler effect method to nitrogen, proposed a method based on measurement of the ion time of flight. Their method, which in fact enables measurement of the mean velocity over a distance of a few inches and along a rectilinear streamline (jet axis for instance) is satisfactory for a low velocity gradient wake. This method has been improved in the Laboratoire d'Aerothermique,[5] first to determine plane but not rectilinear streamlines, and also to measure the real local velocity instead of the mean velocity.

## II. Bütefisch and Venneman's Method

A pulsed electronic beam periodically ionizes the gas at abscissa $x$ of the streamline at time $t=0$; a collector placed at abscissa $x+L$ on this streamline receives the ionized gas at $t>0$ (Fig. 1). If $v(u)$ is the local velocity at abscissa $u$, then, the time of flight, $t$, is given by

$$t=\int_x^{x+L}\frac{du}{v(u)}$$

which enables one to define a mean velocity $v_m(x\to x+L)$ between the abscissas $x$ and $x+L$ by

$$t=\frac{L}{v_m(x\to x+L)}$$

Bütefisch and Vennemann assumed a low gradient $(dv(x)/dx<<1)$; hence for a rectilinear streamline one can assume that

$$v_m(x\to x+L)\simeq v(x)=(L/t)$$

## III. Modified Method

In particular zones (near the Mach disk or near the lateral shocks), the jets show high velocity gradients. In these zones, the previous method cannot be used. A strict local value of velocity must be derived and can be obtained experimentally, by three different experimental methods, all of which use *derivatives of a function*

a) the collector and beam can be moved together ($L=$const) along the axis. If the group "beam-collector" is moved by $\Delta x$ one has

$$t(x+\Delta x)=\int_{x+\Delta x}^{x+\Delta x+L}\frac{du}{v(u)}$$

Thus

$$t(x+\Delta x)-t(x)=\int_{x+\Delta x}^{x+\Delta x+L}\frac{du}{v(u)}-\int_x^{x+L}\frac{du}{v(u)}$$

$$=\int_{x+L}^{x+L+\Delta x}\frac{du}{v(u)}-\int_x^{x+\Delta x}\frac{du}{v(u)}$$

which becomes the limit

$$\lim_{\Delta x\to 0}\frac{t(x+\Delta x)-t(x)}{\Delta x}=\left[\frac{dt}{dx}=\frac{1}{v(x+L)}-\frac{1}{v(x)}\right](^*)$$

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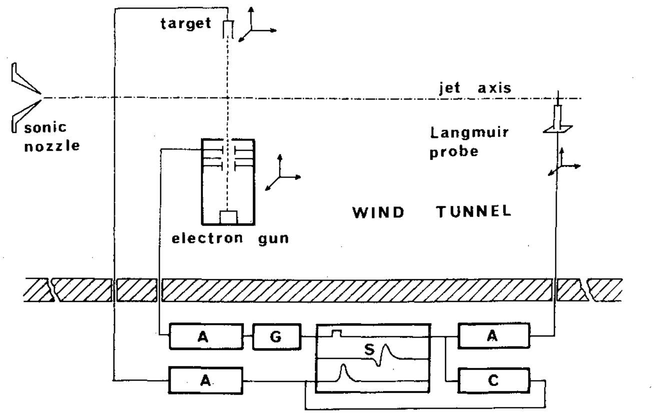


**Fig. 1 Schematic of experimental arrangement: $A$ = amplified, $G$ = pulse generator; $S$ = dual trace scope; and $C$ = time counter.**

This relationship can be interesting if $v(x)$ is known accuractely at one point, because in this case the velocity at $x+L$ can be determined from the velocity at $x$.

b) Either of the two components (beam or collector) may remain fixed, and then it is easy to show that the relation (*) is replaced by

$$(dt/dx) = (1/v(x+L)) \qquad \text{(beam unmoved)}$$

$$(dt/dx) = -(1/v(x) \qquad \text{(collector unmoved)}$$

These results may only be used along a rectilinear streamline.

## IV. Case of a Plane Nonrectilinear Streamline

In this case, only the following assumptions are made: the plane streamline is the graph of a continuously differentiable function of $x$, and it crosses the beam at point $A$. Formulas of the previous paragraph $b$ are generalized by replacing abscissa $x$ by curvilinear abscissa $s_B$ of $B$ measured from $A$ along the streamline, and hence become, if the beam is fixed

$$(dt/ds_B) = 1/v(B)$$

The use of this relation differ as to whether the streamline passing by $B$ is already known or not. If the streamline is known, the beam is left unmoved at $A$ and the collector is moved along the streamline giving $t(s_B)$. If the streamline is not known (which means also $dB$) one can still write in Cartesian coordinates

$$\frac{\Delta X}{u(X,Y)} = \frac{\Delta Y}{v(X,Y)} = \frac{\Delta s_B}{v(s_B)} = \Delta t$$

where $X$, $Y$ are the coordinates of $B$, $u(X,Y)$ and $v(X,Y)$ the velocity components at $B$.

Let us place the beam at the origin 0, source point of the flow, located at a distance equal to two throat diameters downstream from the throat of the nozzle: all streamlines meet at 0; hence

$$u(X,Y) = \dot{X}(t) = \lim_{\Delta t \to 0} \frac{\Delta X}{\Delta t} \qquad v(X,Y) = \mathring{Y}(t) = \lim_{\Delta t \to 0} \frac{\Delta Y}{\Delta t}$$

When the collector is moved in a direction parallel to the $x$-axis (for instance), a graph of flight duration $t(x)$ in the neighborhood of $B$ may be plotted, the slope of which at $B$ gives us the velocity component at $B$

$$\tan \alpha = u(X_B, Y_B)$$

In actual fact, using this method, it is not possible to determine with accuracy small components (< 50 m/sec) which is the case for $v(X,Y)$ in several zones of the wake. For this reason streamlines are first determined by a method described in the following.

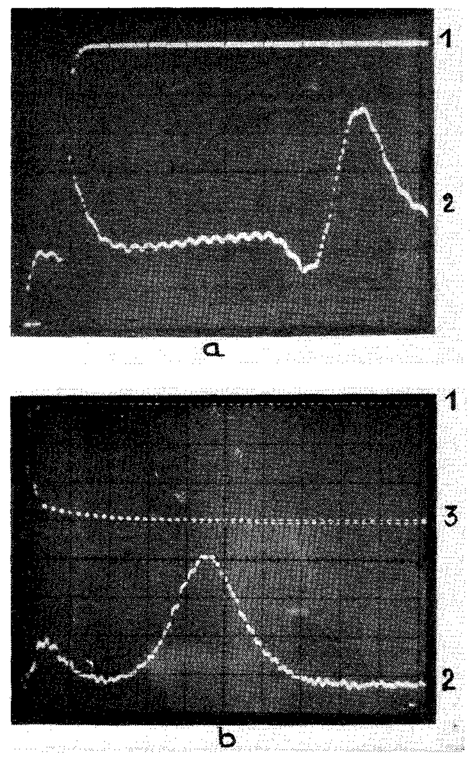


**Fig. 2 Oscilloscope photographs, a) $t = 75$ $\mu$s and b) $t = 45$ $\mu$s. 1 = first pulse on deflection plates; 2 = Langmuir probe signal; and 3 = target signal.**

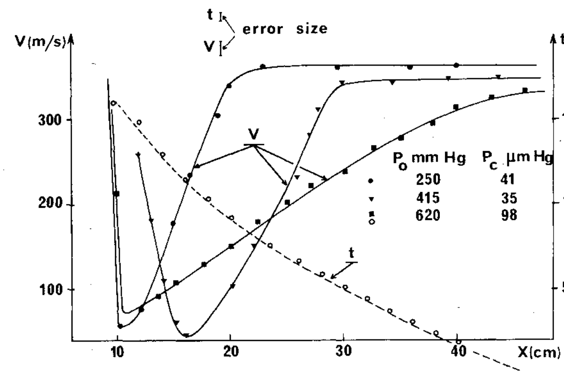


**Fig. 3 Flight duration of the ionized particle from the beam to the Langmuir probe and velocity values in the jet.**

## V. Experimental

In Fig. 1, at the output of the electron beam used to measure the other quantities (density, rotation temperature), the beam is deviated by deflexion plates so as to prevent it from going through the orifice. Other deflexion plates, supplied by a pulse generator, pulse the beam and periodically bring it back into the orifice. The particles ionized by the pulsed beam are received at a distance $L$ by a Langmuir probe made with a simple tungsten wire 3 mm long and 0.5 mm in diameter. The electron beam and Langmuir probe are both set on a Cartesian support permitting all movements. After amplification, the current received, the pulses and the target current are recorded on a multichannel oscilloscope (Fig. 2) making it possible to measure the time $t$ taken by the ionized particle to cover the distance $L$. A frequency meter and time recorder give an accurate value of time $t$. It is this value $t$ which is used in the formulas of the previous paragraph.

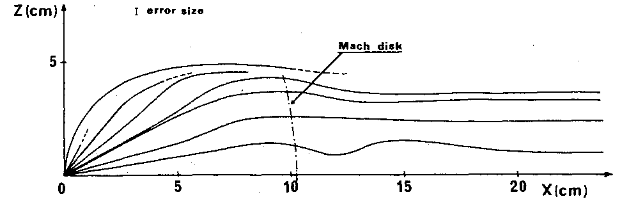


Fig. 4 Jet streamlines; — · — · —Mach disk.

## VI. Axial Measurements and Results

Upstream from the Mach disk and on the jet axis, velocities reach the limit value $u_\ell$ very near the orifice (at a distance about 3 times the throat diameter); $u_\ell = 770$ m/sec for a diatomic gas and for temperatures reaching about 293 K.

Immediately after the disk, it is possible to estimate the approximate velocity by comparing this disk to a normal hypersonic shock. The Mach number just after this shock thus reaches the limit value: $M_2 = [(\gamma = 1)/2\gamma]^{1/2}$ the temperature measured in this zone being about the same as the temperature in reservoir $T_c$: the velocity is given by

$$u^2 = RT_c[(\gamma - 1)/2]$$

($u \neq 130$ m/sec if $\gamma = 1{,}4$ and $T_c = 293$ K).

When the characteristic Reynolds number

$$\mathrm{Re} = kd[P_0 P_c]^{1/2}$$

with stagnation pressure $P_0$ in Torr, chamber pressure $P_c$ in Torr, $d$ in meters, and $k = 3 \times 10^4$, is high, measurements show relatively good agreement with this order of magnitude. For smaller Reynolds numbers, the measured velocity is found to be lower.

Finally, for the lowest values of *Re*, velocity measurements become impossible in a more or less wide zone downstream of the disk. In fact, one can verify that the signal received near the Langmuir probe is unstable and exhibits a very smooth maximum.

In any case, there is a distance associated with the Reynolds number from which it is possible to measure velocities downstream from the Mach disk. This distance increases with decreasing Reynolds number, i.e., as local velocities decrease $< 100$ m/sec); as a matter of fact, the ionized fluid particle, the initial volume of which is about 5 $mm^3$, then has a velocity sufficiently low so that the diffusion phenomena are no longer negligible during the beam travel to the probe. The ion concentration around this probe becomes too small in relation to its sensitivity. It may seem possible to obtain an adequate ion density by reducing the distance between the beam and the probe. In fact, measurement remains impossible owing to another problem arising from interaction between beam and probe. The probe in fact catches part of the electrons coming from the beam,[6] and thus constitutes a barrier to the ionized particles.

Figure 3 shows one of the flight duration $t(x)$ curves obtained for the jet with parameters $P_0 = 62$ cm Hg (generating pressure) $P_c = 98$ $\mu$Hg. On the same figure are plotted to the velocities, in terms of abscissa $x$, for three different jets. The characteristics of the jets experimented are shown in Table 1.

Table 1 Pressures corresponding to the three jets experimented

| $P_0$ (cmHg) | $P_c$ ($\mu$Hg) |
|---|---|
| 62 | 98 |
| 41.5 | 35 |
| 25 | 41 |

One finds that the greatest slope of the velocity curves is a decreasing function of Reynolds number as previously defined. At infinity the curves seem to reach the same asymptotic value, about that of the sonic velocity relative to downstream conditions.

## VII. Results Out of the Jet Axis

The electronic beam is always horizontal and perpendicular to the axis of the jet and can be moved by $x$ or $z$ translation. The streamline $(x_0, 0, z_0)$ where the beam crosses the vertical meridian plane of the jet is obtained, point after point, by moving the Langmuir probe vertically for every fixed value of abscissa $x$, so as to obtain maximum amplitude for the received signal. When precision of measurement is sufficient because of the large distance between the probe and the beam, and because of the diffusion of ionized fluid particles, the beam is moved to an already known point of the streamline.

In Fig. 4 it can be seen that the streamlines can be arranged into two groups, one going through the Mach disk, the second feeding the barrel shock. The Mach disk has been located by a previous density exploration. The former are included inside a cone the axis of which is the axis of the jet, with a half angle of about 27°. The lines inside the cone are initially radial straight lines (according to source flow) and are then inclined towards the axis far upstream of the Mach disk; downstream of the Mach disk they quickly become parallel to the axis. The lines outside of the cone are also straight lines and are inclined towards the barrel shock in order to feed it.

One can observe on a jet exhibiting a large Reynolds number, that the streamline leaving from the triple point (slipline) is practically parallel to the axis, this line being also approximately the line of maximum density and velocity. Consequently, most of the flow passes in the vicinity of this streamline, providing experimental confirmation of Sherman's model given by a source flow distribution close to the axis. This distribution implies that a relatively small part of the flow crosses the Mach disk. Moreover, for increasingly smaller Reynolds numbers, the slipline is less and less visible, the outer flow rapidly reaching the axial zone.

## VIII. Conclusions

After having measured the densities and rotational temperatures in a free jet, the authors determined the streamlines and local velocities in the same jet. In these conditions, the description of a jet is complete as far as the three usual moments are concerned. Further investigations will be valuable for determining the physical behavior of the gas in such conditions.

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