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An Optical Method of Measuring Flow Velocity in an Arc-Heated Wind Tunnel

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An Optical Method of Measuring Flow Velocity in an Arc-Heated Wind Tunnel

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Summary.

An optical method has been devised to measure velocity in the flow from an arc-heated wind tunnel. This method does not require the knowledge of any flow condition, and it does not interfere with the flow.

Velocity measurements have been made in the flow from the University of Southampton arc-heated wind tunnel using this technique. These results have been compared with the results of a Langmuir probe survey made under the same conditions, and it has been found that they lie within the uncertainty of the Langmuir probe data.

Refinements to the apparatus are suggested.

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Section

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[*] Replaces University of Southampton A.A.S.U. Report No. 262—A.R.C. 26741.

LIST OF FIGURES

1. *Introduction.*

The preliminary results of a survey made in the argon flow from the University of Southampton arc-heated wind tunnel, using Langmuir probes, have been described in Ref. 1. It was suggested in this report that in view of the uncertainty in the analysis of the Langmuir probe data, it would be desirable to make an accurate determination of some flow conditions by an independent method.

When using an earlier version of the plasma torch (Ref. 2), with a cylindrical tungsten cathode concentric with a cylindrical copper anode, it was found, by observing the flow with a photo-multiplier, that the intensity of the light emitted from the flow fluctuated regularly at about 2·5 kc/sec. This fluctuation had been observed in previous torches and in other test gases. The frequency seemed to be dependent upon arc geometry and upon the test gas. This fluctuation corresponded to an oscillation in arc voltage.

It was suggested that if this light intensity oscillation was moving at the flow velocity (*see* Section 6), and if a photo-multiplier were able to follow a moving frame in the flow, then the photo-multiplier would record a Doppler shift in the frequency of the intensity oscillation. This shift could then be used to relate the flow velocity to the known velocity of the moving frame.

A photo-multiplier was therefore set up to study the flow from the present Plasma torch, at first in a stationary frame. It was found that, probably because of the electrode geometry now employed, the high frequency oscillation was no longer present, and the only detectable cyclic fluctuation in intensity was small, and was due to the 300 c/s ripple inherent in the rectified power supply. However by feeding a small sinusoidal current and voltage oscillation to the arc, it was possible to produce a high frequency light intensity oscillation which was easily detected by the photo-multiplier, yet apparently did not alter the flow conditions (*see* Section 5).

The moving reference frame in the flow was generated by setting up the photo-multiplier to observe the flow *via* a rotating mirror.

The apparatus is described in detail in Sections 3 and 4 below.

2. *The Arc-Heated Wind Tunnel and Operating Conditions.*

The wind tunnel and the plasma torch are described in detail in Ref. 1. For the work described in the present paper the electrodes used in the torch, Fig. 1, were the same as those used during the Langmuir probe survey (Ref. 1), i.e. a sharply pointed tungsten cathode concentric with a tapered copper anode.

The same operating conditions were also used and these may be summarised as follows:

Test gas	Argon
Mass flow	10 gm/min
Arc current (D.C. mean)	260 A
Arc voltage (D.C. mean)	13·5 V
Arc chamber pressure	330 mm Hg
Plenum	304 mm Hg
Vacuum tank pressure (mean)	28 μ Hg

If it were permissible to neglect the boundary layer thickness at the throat of the nozzle, the reservoir temperature (T_0) at the given mass flow would be 5200 deg K. However, following Cohen and Reshotko (Ref. 3) and Monaghan (Ref. 4), an estimation of the displacement thickness at the throat has been made. This indicates that the reservoir temperature is 8200 deg K ± 300 deg K. The value of 8200 deg K has been used herein.

It is now thought that the pressure in the centre of the nozzle exit plane is appreciably higher than the vacuum tank pressure. Using the estimated value of 100 μ Hg, and from experimental pitot traverses in the nozzle exit, the Mach number on the nozzle exit plane centre line is taken as 6·4.

On the crude assumption that the expanding flow through the nozzle can be described by the isentropic ideal gas equation, we find that where $M = 6{\cdot}4$, the ion thermal velocity would be 10^5 cm/sec and the flow velocity at the nozzle exit plane (U) would be 3×10^5 cm/sec. Previous experimental results ~~(Ref. 1)~~ suggest that the flow velocity is less than this.

3. *The Optical System.*

A schematic diagram of the optical system is shown in Fig. 2. The mirror used to generate the moving reference frame was 1 cm. wide and 3 cm. high, and was mounted on the spindle of an electric motor, so that it could rotate about a vertical axis through its centre. The speed of the motor was controlled through a Variac. The centre of the mirror was 90 cm from the centreline of the nozzle of the Plasma torch. A photo-multiplier, well shrouded from extraneous light was aligned and collimated through two slits onto the centreline of the mirror. The collimation was such that the reference plane in the flow to which the photo-multiplier responds was 4 mm wide and 15 mm high, symmetrical about the nozzle centreline (Fig. 3a).

The output of the photo-multiplier was passed through a Cawkell band pass filter, type FU4, into a Tektronix type 545 A oscilloscope. The oscilloscope was set to trigger a single trace as the reference plane passed the nozzle exit plane, and the trace was recorded on a Polaroid Land oscilloscope camera.

As can be seen in Fig. 9a the basic shape of the trace is a sudden rise as the reference plane passed into the nozzle exit plane followed by a decay as the reference plane passes down the expanding flow. The high frequency oscillation is superimposed upon this transient. It was hoped that the transient, being of low frequency, could be eliminated by suitable adjustment of the band pass filter. However, the filter reacted to the steep transient with a decaying oscillation instead of a sharp cut off.

To overcome this the low frequency cut off of the filter was removed, and was replaced by a wedge shaped optical filter between the flow and the mirror (Fig. 3b). The effect of this was to reduce the initial transient and to give a more constant output from the photo-multiplier, since the effective height of the reference plane increased to pick up more light as the plane moved into the cooler gas. It was assumed that the cool gas between the central intense core of the plasma and the mirror had a negligibly small effect on the photo-multiplier.

To justify this assumption, a radial sweep across the plasma was made as shown in Fig. 4a. The form of the resulting oscilloscope trace is shown in Fig. 4b and Fig. 8a. It can be seen that the central core of the plasma dominated the intensity of light from the flow.

Since the frequency of the intensity oscillation was measured over one to two cycles, it is seen that the measured velocity is the average value over about 4 cm of the flow.

The volume of gas over which the flow velocity has been determined can therefore be represented as shown in Fig. 5.

4. *The High Frequency Input Signal.*

The circuit which was used to feed a high frequency ripple of about 6A into the arc current of 260 A. D.C., is shown in Fig. 6. A Heathkit Model AG-9U Audio Generator, capable of delivering 3V r.m.s., fed the signal at the desired frequency into a 100W amplifier. This was capable of passing a sinusoidal current of up to 8A amplitude through a 16 μ F capacitor into the torch electrodes.

5. *Operation of the Velocity Measuring Apparatus.*

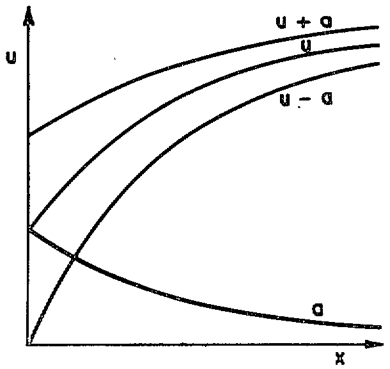
The flow was observed through a stationary reference frame with the photo-multiplier to determine the amplitude and frequency of the intensity oscillation produced by feeding a small alternating current to the arc. It was found that the amplitude of the intensity oscillation varied considerably with frequency for an input signal of constant amplitude. The change of amplitude with frequency was non-linear, and it was found that certain frequencies gave rise to what might be a type of resonance in the arc or the arc circuit, producing a large amplitude of light intensity oscillation. This happened, in particular, at about 6 kc/sec and, to a lesser extent, at about 12 kc/sec. Owing to the difficulty of separating the signal from the noise at higher frequencies, it was decided to use an input signal of about 6 kc/sec for most of the velocity measurements, since this gave the optimum output/input amplitude ratio.

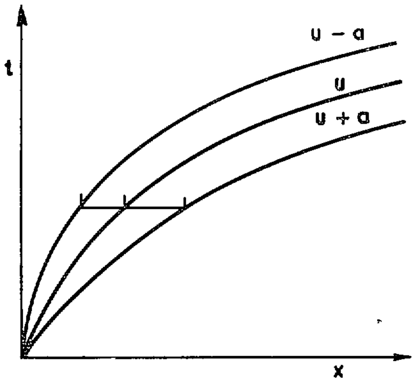
It was found desirable to keep the input signal as small as possible to avoid disturbing the arc conditions. In fact, it was found that input signals with an amplitude greater than about 7 or 8 A did cause a sudden slight decrease in arc and plenum chamber pressure. For all measurements the amplitude of the input signal was kept below 5 A, i.e. below about 2 per cent of the D.C. level, and no alteration in any macroscopic flow conditions was detected.

The rotating mirror could only sweep about 20 cm of the flow, and the duration of the sweep obviously decreased as the mirror rotation speed increased. Since the apparent wavelength of the intensity oscillation increased with mirror speed, this apparent wavelength approached, and could exceed the sweep duration as the mirror speed was increased. Hence there was a limited range of mirror speeds which would give a useful trace.

In practice, the mirror speed and oscilloscope time scales were adjusted simultaneously until a suitable trace was obtained. This trace would be recorded, and immediately the time scale would be increased to give a trace from which the mirror rotation speed could be determined.

6. *The Velocity of the Intensity Oscillation.*





We have assumed that the oscillation in intensity is travelling at flow velocity. To justify this let us consider the form of the velocity (u) against distance (x), and of the x *vs.* t diagrams for the flow, which are sketched above and in which secondary waves are ignored. Suppose that a disturbance imposed at time $t = 0$ generates backward and forward facing waves, which travel at the local sound speed (a) relative to the fluid. From the x *vs.* t diagram it is seen that, on the non-linear portion of the curves, at any instant, the backward and forward facing waves have not in general travelled equal distances from a gas element travelling at velocity u. If these waves appreciably affect the intensity of light emission, we should expect that the wave pattern seen by the photo-multiplier would be distorted, and that this distortion would change with distance along the flow. It can be seen from Fig. 8b, which is a photo-multiplier record taken in a stationary reference frame, that there is no noticeable distortion of the wave pattern. A photo-multiplier record taken in a moving reference frame (Fig. 9), does not show any obvious distortion at other stations in the flow. This evidence has been taken to justify the assumption that the oscillation in intensity which is recorded on the photo-multiplier is travelling at flow velocity.

7. *Analysis of Velocity Measurements.*

In Fig. 2b, P is the intersection of the reference plane with the nozzle centreline, and M is the vertical mirror centreline. The distance MP is, say, r cm. Then if the speed of the mirror is n rev/sec, then the angular velocity of the incident beam MP is $2n$ rev/sec. The tangential velocity of P is then $2\pi r \times 2n$. Since the radius r is large compared with the length of flow under consideration, then the tangential velocity of P is approximately equal to the velocity of P along the nozzle centreline. Let the velocity of the flow be U at the nozzle centreline, averaged over the volume shown in Fig. 5. Let the frequency of the intensity oscillation be f c/sec in a stationary frame of reference. We can assume that the oscillation in intensity is travelling at an average velocity U in the region swept by the photo-multiplier reference plane. If the moving reference frame has a velocity v in the direction of the flow, then the apparent wave speed and frequency are $(U-v)$ and f_{app} respectively.

Then

$$\frac{f_{\mathrm{app}}}{f} = \frac{(U-v)}{U}$$

and

$$U = v\frac{f}{f-f_{\mathrm{app}}} = v\frac{f}{\Delta f}$$

$$= 4\pi rn\frac{f}{\Delta f}$$

Both n and f_{app} were determined from an oscilloscope trace.

8. *Experimental Results and their Accuracy.*

We are concerned only with the accuracy with which n and f_{app} can be determined. Even from an oscilloscope trace, the mirror speed, n, can be determined quite accurately, so we are only concerned with the accuracy with which the apparent frequency change can be measured. As the mirror speed increases, the accuracy with which f_{app} can be measured decreases, since the sweep duration approaches one, or less than one, apparent cycle of the intensity oscillation.

The frequency measurement, under these conditions, has to be made over only one cycle, thereby reducing its accuracy.

On the other hand, at low mirror speeds, f_{app} approaches f, so that Δf is very small, and its accuracy is therefore poor.

Thus there is some optimum value of mirror rotation speed (n) which falls between these limits. For the optical system used in this experiment, and for the usual input signal frequency of 5·7 kc/sec, the range of mirror speed for optimum accuracy was about 10 to 20 rev/sec. Within this range the accuracy of the flow velocity, (U), determined from the probable errors in the reading of the oscilloscope traces, was about ± 15 per cent.

At mirror speeds below about 4c/sec and above 28 c/sec the accuracy could not be better than ± 25 per cent.

Most readings were therefore taken with the mirror rotation speed in the range 10 to 20 c/sec, and all experimental results fall within the probable error band (Fig. 7). From the results shown in Fig. 7, the average velocity at the nozzle centreline, over an area not greater than that shown in Fig. 5, has been determined as $1{\cdot}2 \times 10^5$ cm/sec. It should be emphasised that this is an average velocity.

The only other apparent source of inaccuracy was the possibility that a change of input signal frequency could affect the flow velocity or the velocity measurement. Several measurements were made at frequencies other than 5·7 kc/sec, and although the accuracy of these readings was poor, the values of velocity determined from these readings agreed, within their error band, with measurements made at 5·7 kc/sec.

9. *Refinements to the Method.*

This experiment was intended to be used as a check upon Langmuir probe measurements, and the apparatus was kept as simple as possible without undue sacrifice of accuracy. If the following modifications were made to the basic apparatus described in this report, then it could be possible to use the method as a major diagnostic tool in the study of a luminous flowing plasma.

(*a*) As shown in Section 8 above, the accuracy of the velocity measurement is largely dependent upon the accuracy with which the apparent frequency of the intensity oscillation can be determined. The signal/noise ratio of the electronic apparatus used in this experiment made it necessary to use an input signal frequency below about 10 kc/sec. If the frequency of the input signal were increased, while retaining a good signal/noise ratio from the photo-multiplier, the accuracy of the method would be increased since (i) the mirror rotation speed could be increased, so that the accuracy of the quantity Δf would be increased, and (ii) since the wavelength of the intensity would be decreased, the velocity could be averaged over a much smaller length of flow.

By using a high frequency input signal, then several cycles could be observed during a sweep of the mirror, and it would be possible to estimate the change of velocity with distance down the flow.

(*b*) By using a condensing lens system to focus a point in the plasma onto the slit of the photo-multiplier, instead of the slit collimation used in this experiment, the velocity could be determined over a much smaller area of the flow. It should then be possible to sweep along selected lines in the flow, and this technique, combined with the possibility outlined above of measuring velocity change along the flow, would enable a survey of velocity to be made throughout the flow.

(*c*) In the present work a crude wedge shaped optical filter has been used to reduce the transient as the reference plane enters the luminous area. By using a graded optical filter instead of a wedge, the transient could be considerably reduced. It would then be possible to use a sharp cut off band pass filter on the photo-multiplier output, which, in conjunction with a frequency counter would give a more accurate measurement of f_{app} than can be obtained from an oscilloscope trace.

It is suggested that the method described in this report for measuring velocity in a flowing plasma, together with the modifications outlined above, could be used to measure flow velocity to an accuracy better than 15 per cent. This velocity could be averaged over a very small area at any point in the luminous flow.

10. *Comparison with Langmuir Probe Results.*

Measurements of flow velocity at the nozzle exit plane centreline have already been made with Langmuir probes in the University of Southampton plasma jet (Ref. 1).

Following Clayden (Ref. 5) it was initially assumed that, in a plasma where the flow velocity is much greater than the ion thermal velocity, electrons cannot penetrate the wake of a spherical probe, due to ambipolar diffusion. Consequently, it was assumed that the effective collecting area of a spherical probe, under these conditions, was the upstream hemisphere of the probe. Using this assumption, the flow velocity determined from Langmuir probe results was 5×10^4 cm/sec (± 10 per cent).

However, a comparison of spherical and cylindrical probes suggested that the effective electron collecting area of the spherical probe was the total area of the sphere. Using this area, the spherical probes gave a velocity of 1×10^5 cm/sec (± 10 per cent).

It is seen that this latter result is in better agreement with the velocity obtained by the optical method, i.e. $1 \cdot 2 \times 10^5$ cm/sec (± 15 per cent).

This could indicate that the effective electron collecting area of the spherical Langmuir probes described in Ref. 1 is the total area of the sphere, and that the probe sting causes considerable interference with the wake from the spherical electrode.

New techniques have now been devised for making 'free molecule flow' Langmuir probes, which have eliminated the sting interference. Results from these probes support the suggestion that the probes described in Ref. 1 collect electrons over the total spherical surface.

11. *Conclusions.*

1. An optical method has been devised to measure velocities in the flow from an arc heated wind tunnel, which does not disturb the flow, and does not depend upon other measurements. Using this technique, a mean flow velocity of $1 \cdot 2 \times 10^5$ cm/sec ($\pm$ 15 per cent) was recorded at the centre of the nozzle exit of the University of Southampton plasma jet wind tunnel.

For isentropic, perfect gas flow from the estimated reservoir conditions, this velocity would be 3×10^5 cm/sec, when the displacement area of the boundary layer at the throat is neglected.

2. Data obtained using spherical Langmuir probes (Ref. 1) gives a corresponding velocity of 5×10^4 cm/sec if only the front half of the sphere is effective in collecting electrons, and 1×10^5 cm/sec if the whole surface of the probe is effective. It is concluded from a comparison of the Langmuir probe and optical measurements that the whole surface of these particular probes is effective in collecting electrons, probably because of sting interference.

A comparison of spherical and cylindrical Langmuir probe data led to the same conclusion.

Langmuir probes of the spherical type, free from sting interference have recently been used, and results from these probes support the foregoing comments.

3. Refinements to the apparatus have been suggested to improve the accuracy of the optical method of flow velocity measurement.

Acknowledgements.

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The author is indebted to Mr. P. L. Tanner for his advice and assistance in the setting up of the electronic equipment.

LIST OF SYMBOLS

U	Flow velocity averaged over volume shown in Fig. 5
u	Local flow velocity
a	Local sound speed
v	Velocity of moving reference frame
x	Distance co-ord. in flow direction $x = 0$ at nozzle throat
r	Distance from rotating mirror to nozzle centreline
n	Mirror rotation speed
f	Frequency of intensity oscillation in stationary reference frame
f_{app}	Apparent frequency of intensity oscillation in moving reference frame
Δf	$(f - f_{\text{app}})$

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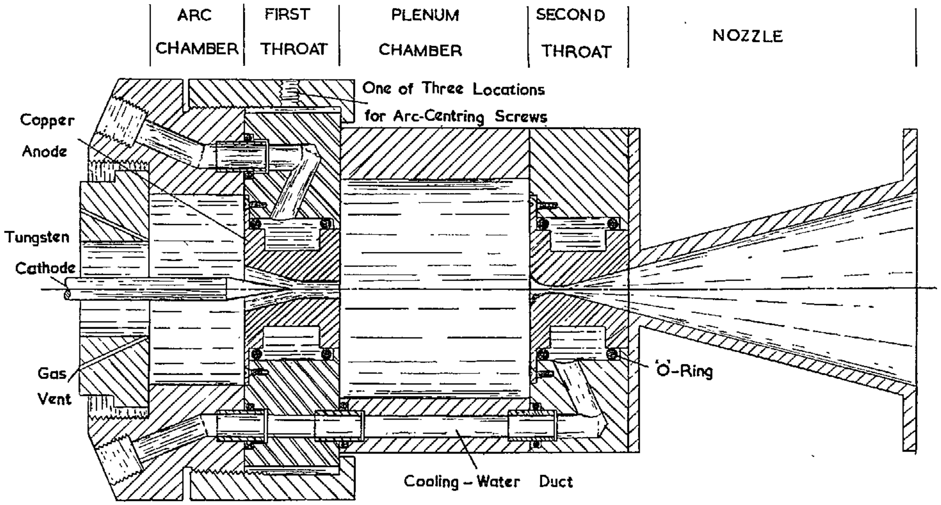


FIG. 1. A section of the Mark IV torch.

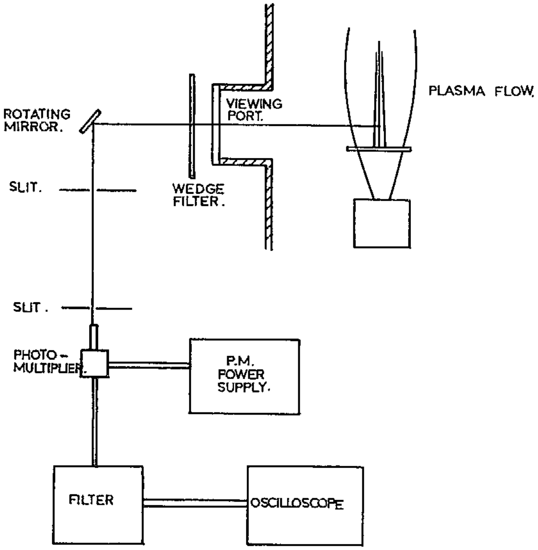


Fig. 2a. Schematic layout of optical system.

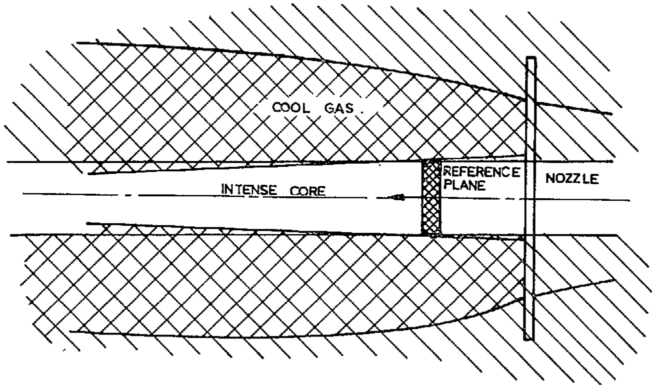


Fig. 3a. Collimation of photo-multiplier slits and moving reference plane.

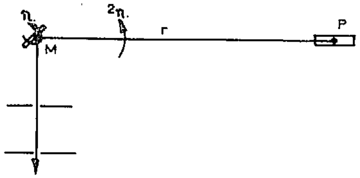


Fig. 2b. Nomenclature of optical system.

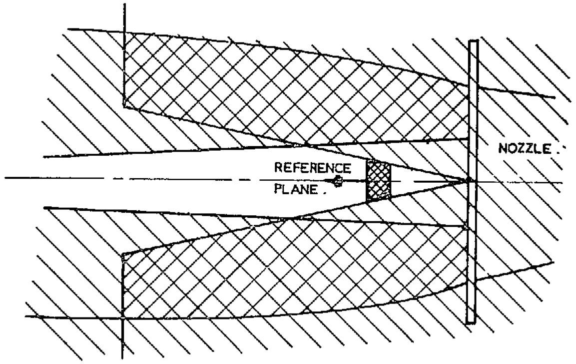


Fig. 3b. Optical wedge filter.

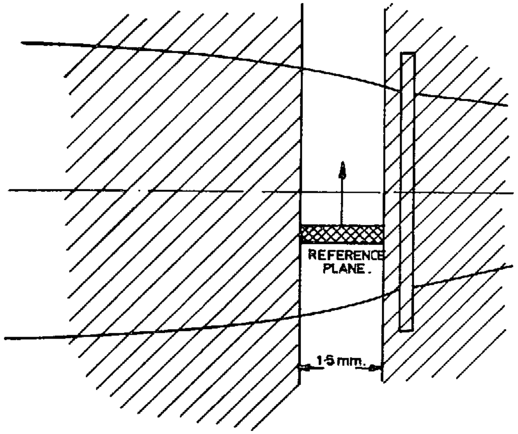


FIG. 4a. Radial sweep of flow.

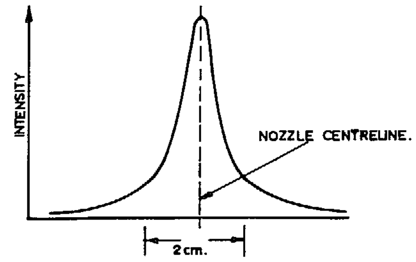


FIG. 4b. Radial intensity distribution.

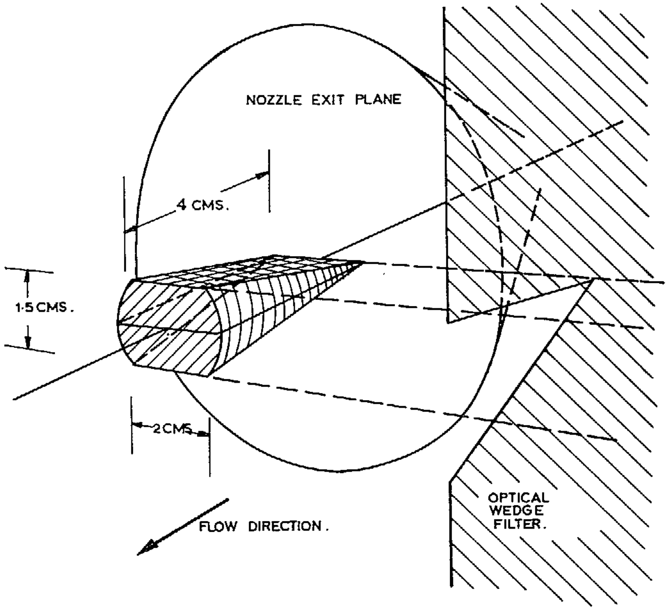


FIG. 5. Maximum volume of flow in which the average velocity has been determined.

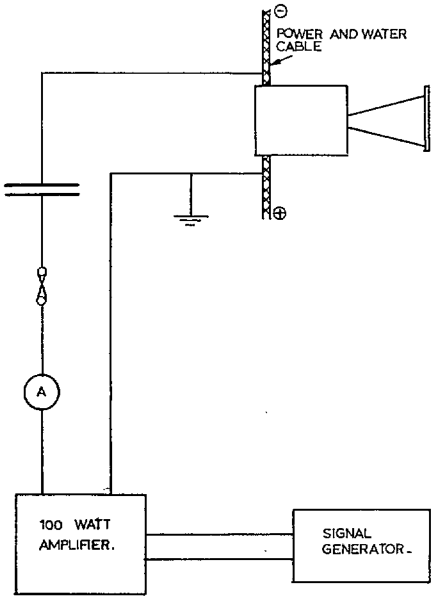


FIG. 6. Input signal circuit diagram.

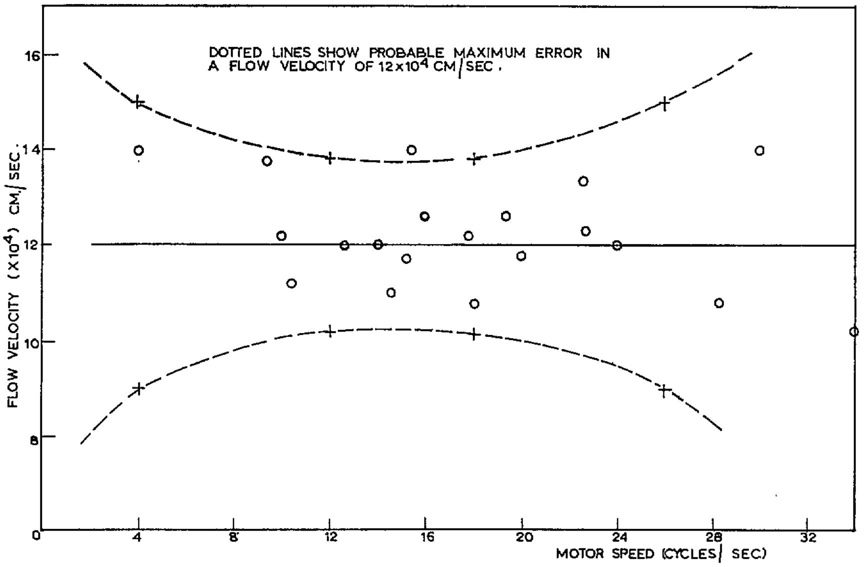
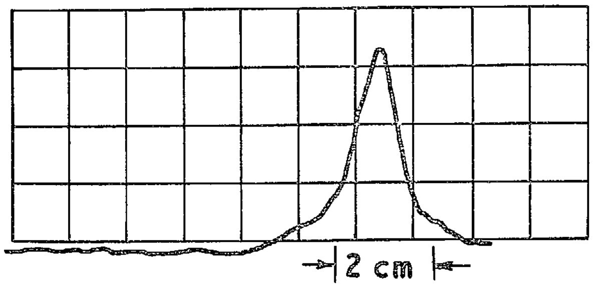
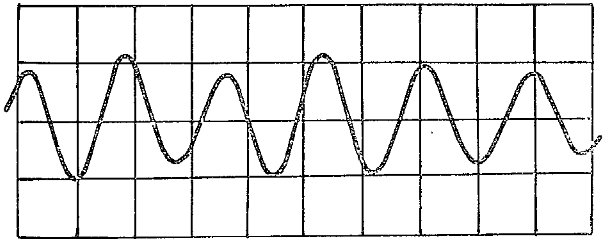


FIG. 7. Experimental results.

(94160) Dd. 125874 K.5 9/66 Hw.



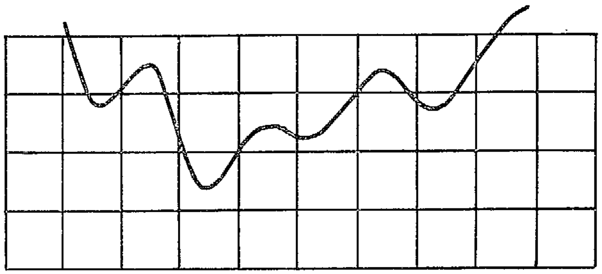
(a) Radial intensity distribution



Horizontal scale 105 $\mu s/cm$

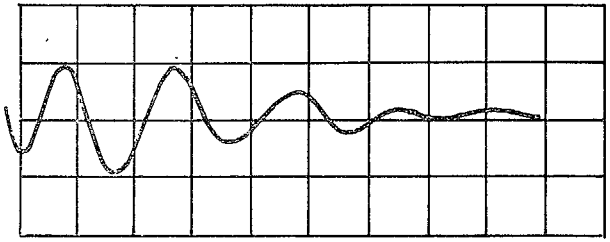
(b) Photomultiplier record in a stationary reference frame

FIG. 8



Horizontal scale 105 $\mu s/cm$

(a) Record in moving reference plane. No wedge filter



Horizontal scale 105 $\mu s/cm$

(b) Record in moving reference plane with wedge filter

FIG. 9

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