J. Fluid Mech. (1964), *vol.* 20, *part* 2, *pp.* 183–192
Printed in Great Britain

A new technique for the measurement of low fluid velocities

By M. GASTER*

Nuclear Engineering Department, Queen Mary College, London

(Received 25 July 1962 and in revised form 19 March 1964)

A new instrument for measuring the velocities of particles suspended in a flowing fluid is described. The instrument is linear and is therefore capable of measuring the mean velocity in a fluctuating stream, even when these fluctuations are greater than this mean value. This particular instrument was developed for free convection work where the velocities to be measured were in the range $+0{\cdot}2$ in./sec to $-0{\cdot}2$ in./sec, but there seems to be no reason why this range could not be considerably extended.

1. Introduction

The measurement of low velocities of the order of 10^{-2} ft./sec in liquid flows presents a difficult instrumentation problem and although various techniques have been developed to deal with specific problems none was suitable for the convection experiment carried out by the writer. A new type of instrument was therefore devised to cope with some of the problems peculiar to this convection work. This instrument uses an extremely flexible technique which should be capable of being adapted to suit a wide range of flows.

2. Principle of the instrument

The instrument measures the velocity of small particles suspended in the flow. Provided these particles are small compared with the size of the flow structure and have a density near that of the fluid, it will be assumed that they follow the flow sufficiently closely to enable the mean fluid velocity to be given by the mean speed of these randomly distributed particles.

Consider a small element of the flow containing one slowly moving spherical particle illuminated by a beam of light. If the light reflected from this particle is focused onto a transmission grating having a sinusoidal density distribution, the quantity of light passing through the grating will oscillate sinusoidally as the particle image passes over the grating. The frequency of the electrical signal produced by a suitably placed photo-cell is determined solely by the number of grating wavelengths crossed by the particle image in a given time. For a given grating this frequency is directly proportional to the velocity of the particle image normal to the lines. Thus the speed of a particle can be obtained from the ratio of the number of cycles arising from the passage of one image across the grating and the duration of this signal.

---

* Now at The College of Aeronautics, Cranfield.

The photo-cell can be made to monitor the particles within some small volume of the flow by fitting a mask over the grating and illuminating only a narrow slice of flow normal to the viewing direction. Provided the particles are randomly distributed it can be shown that the relative probabilities of one, two or three particles being in view at a time are n, n^2 and n^3 respectively for small values of n. So that if n is sufficiently small the photo-cell output will largely consist of signals produced by isolated particles. Let us first therefore consider the processing required to deal with the major portion of the signal which arises from isolated particles. Later the more complicated signals produced by two or more particles will be discussed.

The signal produced by a series of single-particle images passing over the unmasked area of the grating will be composed of a number of short wave trains, each pulse of waves containing waves having a frequency proportional to the speed of the particle in view at that instant. The mean frequency of the signal, and therefore the mean image velocity, is given by the ratio of the number of cycles occurring in some period and the portion of this period which has particles in view. These two quantities are easily obtained in a digital form using standard pulse circuit techniques. Pulses are formed at every zero of the signal and these are fed to a counter via a gate circuit. The amplitude of the photo-cell signal is used to control this gate, so that pulses are only counted when the signal is greater than some predetermined threshold level. Since counting only takes place when the gate is open, the sum of all these periods can easily be obtained by counting a standard pulse rate through a second gate circuit. This second gate valve is also driven by the signal which operates the first gate so that both circuits remain open for identical periods.

In each pulse train there can be an error of plus or minus one count, but this error can be made insignificant by taking a sufficiently large number of samples.

This idealized form of instrument, operating only on signals generated by single particles, will give a true mean velocity because the system is a linear one—the instantaneous pulse rate is directly proportional to the fluid velocity at the instant that the particle crosses the masked area. By carrying out these counting processes for a sufficiently long period a true mean value can be obtained even in turbulent flows. However, in extremely turbulent flows, where the fluctuations are comparable with the local mean velocity, there may be regions where the flow direction changes sign. The simple instrument with a fixed grating is not capable of sensing the sign of flow and it would therefore indicate quite an incorrect mean value under these conditions. This difficulty may be overcome by moving the grating so that the relative motion of the particle image and the grating lines is always of one sign and a true mean value of velocity relative to the grid can then be obtained. The actual speed is found on subtracting the steady grating speed.

At first it appears that the accuracy of the system can be improved by moving the grating in order to increase the signal frequency and thus the number of pulses arising out of each particle as it crosses the measuring zone. Although the accuracy in measuring the signal frequency rises, the counting errors in obtaining the actual particle speed (relative velocity minus grating velocity) remain the same for all grating velocities. Nevertheless, later it will be shown that certain advantages are gained by using a relatively high grating speed so that the signal frequency fluctuates about some known constant value fixed by the speed of the grating lines.

Now let us discuss the signal produced by two or more particles passing through the measuring zone simultaneously. Consider the case of two particles of similar size and brightness having velocity components v_1 and v_2 relative to the grating. The photo-cell output for these particles will be

$$\sin(2\pi v_1/\lambda + \phi_1) \quad \text{and} \quad \sin(2\pi v_2/\lambda + \phi_2),$$

respectively, where λ is the grating wavelength and ϕ the phase angle of the signal. The overall output is composed of the sum of these signals which may be written

$$2\sin[(2\pi/\lambda)(v_1+v_2)+\phi_3]\cos[(2\pi/\lambda)(v_1-v_2)+\phi_4].$$

The number of zeros arising in such a signal is given by the sum of the zeros in each of the factors. Thus the apparent velocity obtained by counting all the zero crossings is $\frac{1}{2}(v_1+v_2)+\frac{1}{2}(v_1-v_2)$, or v_1. The instrument operating in this manner, counting every zero crossing, would be biased in favour of the faster particle. However, in order to obtain localized measurements it is clearly necessary to make the sample volume small enough so that variations in velocity in the zone are quite small. Since v_1 and v_2 differ only slightly in such a region the signal is basically a sine wave, $\sin[(2\pi/\lambda)(v_1+v_2)+\phi]$, modulated by the slowly varying cosine term, $\cos[(2\pi/\lambda)(v_1-v_2)+\phi]$. The spurious zero crossing associated with this cosine term occurs when the 'amplitude' of the sine wave is zero. The amplitude controlled gate circuits will close when the cosine term is small so that this form of error is eliminated and the mean counts registered on the scaler units correctly give the mean speed of the particles.

Although it is not possible to extend this simple analysis to cover cases with more than two equally bright particles, or to the equally important case where the brightness or size of the images differ, it is not difficult to see that the sum of any number of randomly phased signals differing slightly in frequency will be an amplitude modulated sinusoid. The carrier frequency of this signal represents the mean velocity of the particle images weighted in some way to the larger brighter particles. This frequency can be correctly measured by counting the zero crossings, provided counting takes place for 'large' signals only.

3. The experimental rig

The investigation was carried out in order to obtain the temperatures, heat transfer rates and fluid velocities occurring in cells containing liquids with internal heat sources, such as arise in certain types of nuclear reactor. The cell, made from a 5 ft. length of 2 in. diameter Perspex tube having a wall thickness of $\frac{1}{8}$ in., was vertically mounted in a square Perspex tank containing cooling water. A sketch of the rig is given in figure 1. Dilute hydrochloric acid ($\frac{1}{2}$ % solution) was used as the cell fluid so that internal heat sources could be simulated by a.c. resistance heating of the electrolyte.

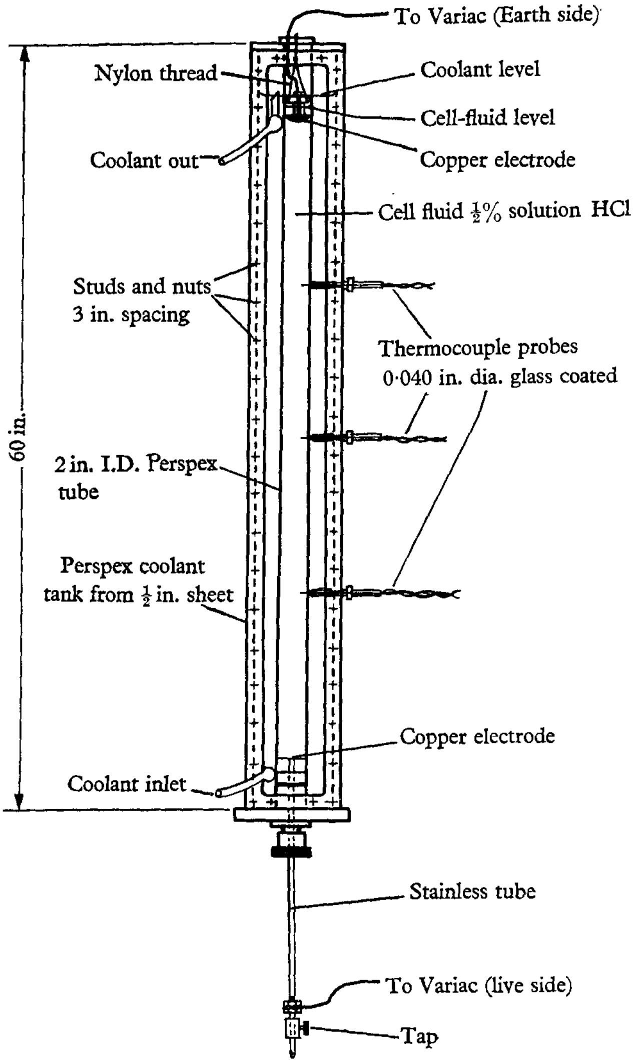


FIGURE 1. Experimental rig.

From observations of the motion of fine dust particles in the cell fluid it was apparent that the velocities in the cell were considerably less than those predicted by the simple laminar theory for infinitely long cells, and in order to obtain the velocity profiles it would be necessary to have an instrument capable of measuring velocities in the range 2×10^{-2} ft./sec to -2×10^{-2} ft./sec with a resolution of about 5×10^{-4} ft./sec.

In addition to the small magnitude of the velocities to be measured there are other difficulties associated with the nature of this particular flow. Even at quite moderate power inputs, when the flow was far from 'turbulent' in the accepted sense, regular low-frequency oscillations disturbed the flow. This disturbance mode, shown in the dye filament photograph in figure 2, plate 1, had the form of a single-start spiral vortex which moved slowly down the tube.

Large low-frequency fluctuations in the flow structure, probably having a similar form to this instability mode, persisted into the turbulent régime which existed at higher heating rates. At points in the mixing region where the mean velocity was small, these disturbances cause the flow periodically to change sign, and in order to find a true mean velocity in an unsteady flow like this, it is necessary to have a directionally sensitive linear instrument which records a mean value over a long sampling period. This latter requirement is necessary as the period of the low-frequency oscillation is of the order of minutes, so that a sampling period of around 20 or 30 min is needed to obtain reasonably accurate results.

4. The experimental instrument

The ideal grating for the instrument would have a sinusoidal density distribution, but the types normally available have rectangular wave forms of various mark-space ratios. Consider the signal generated by a grating of square wave form in place of the assumed sinusoidal type. The Fourier series for a square wave is $\frac{1}{2}+(2/\pi)(\sin x+\frac{1}{3}\sin 3x+\frac{1}{5}\sin 5x\ldots)$, so that even a point light source would produce a signal having relatively small third and fifth harmonic content. The signal generated by a real spherical particle, having an image size roughly equal to the width of a grating line, would be even lower in high-frequency content. In practice it is found that the signal generated by a square grating is closely sinusoidal and no trouble is experienced from the higher harmonics.

In this particular instrument the edge region of a 10 in. radial grating was used. This type of grating approximates to a linear pattern over a small region and has the advantage that the required motion of the grid lines can easily be obtained by rotating the disk. A small synchronous clock motor was used to drive the glass disk by a friction drive on the rim. The grating had a density distribution of square wave form made up from 10800 equal lines and spaces of 0·0013 in. width at a diameter of 9·25 in. The optical system produced a reduced image of the particles on the grid so that the 0·002 in. diameter polystyrene beads used as tracers provided spots of light roughly equal to the size of the grating lines.

The mask, which is required to restrict the area of flow sampled by the instrument, can be placed in contact with a stationary grating. But in the more complex device having a moving grid it is not possible to position the grating and mask sufficiently close together for both to be in focus at once and an additional lens has to be used to overcome this difficulty. See figure 3.

To obtain the actual particle velocity (relative minus grating velocity) it is necessary to know the speed of the grating. This can be found from the frequency of the signal generated by a stationary particle image, or some other fixed spot of light, falling on the grid. In the instrument built by the writer a light source and lens focused a point of light onto a portion of the grid which was well out of the way of the main photo-multiplier and lens system. The transmitted light fell on a second photo-multiplier which provided a continuous sine wave signal having a frequency proportional to the disk speed. The light source, lens and photo-cell were mounted permanently on the disk housing shown in figures 4 and 5, plates 2 and 3.

The grating assembly was free to slide along the line of sight of the instrument so that the device could be focused on any plane in the tube, a screw being provided for fine adjustment. A narrow beam of light, 1 in. high by 0·02 in. wide, was produced by a 250 W compact source mercury vapour lamp and the necessary lenses and slits. This whole assembly was mounted on rails to enable the beam to be traversed across the tube.

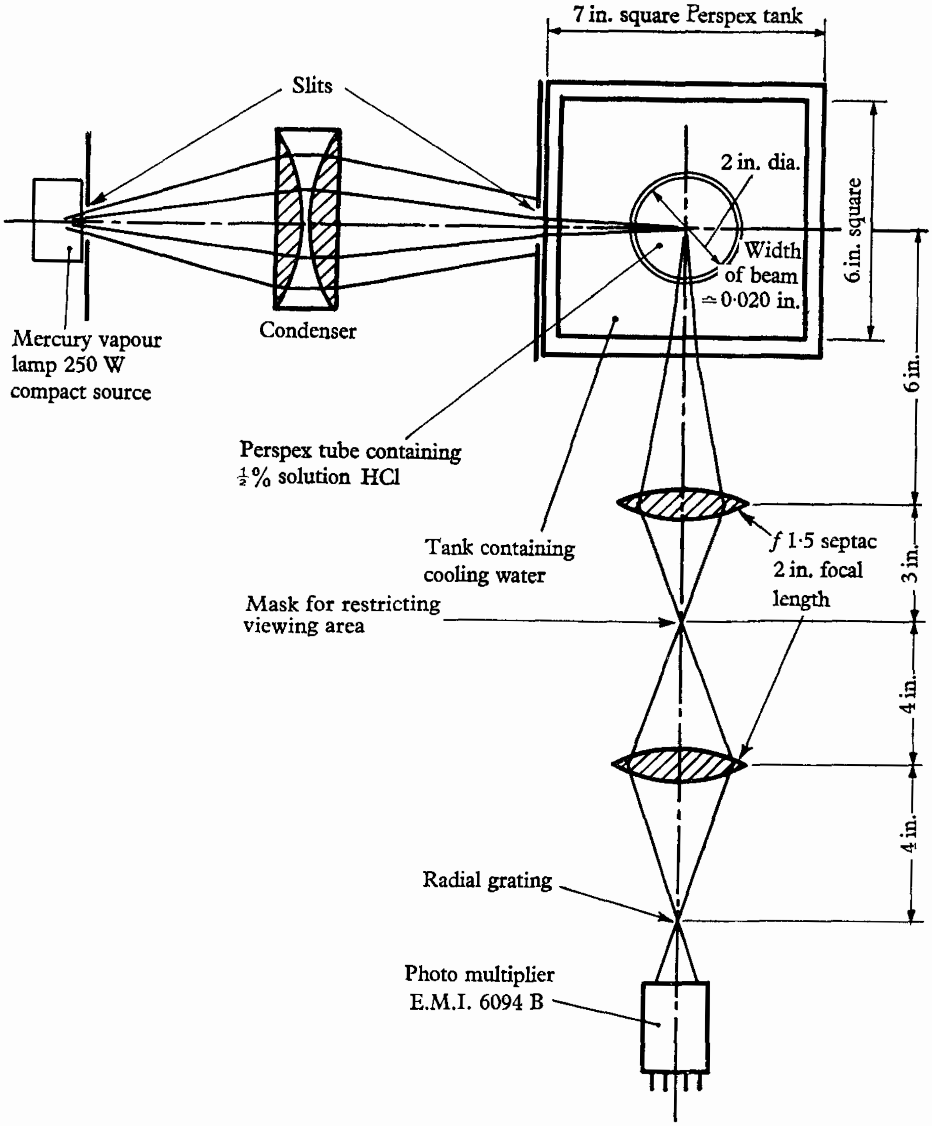


Figure 3. Optical layout for velocity determination.

The block diagram, figure 6, shows the various stages of electronic processing required to convert the photo-cell output into pulse trains. After amplification the signal was filtered by a band-pass unit to remove most of the noise and to clean up the wave-form by removing any harmonics present. Pulses were generated at each zero crossing by differentiation of the rectangular wave output of a Schmitt trigger stage which was fed by the filtered photo-cell signal. However, as these pulses were of alternating sign it was convenient to use only the positive going ones occurring for each cycle of wave-form. Although the instrument described here had this simplification, later versions have been built which count every zero crossing.

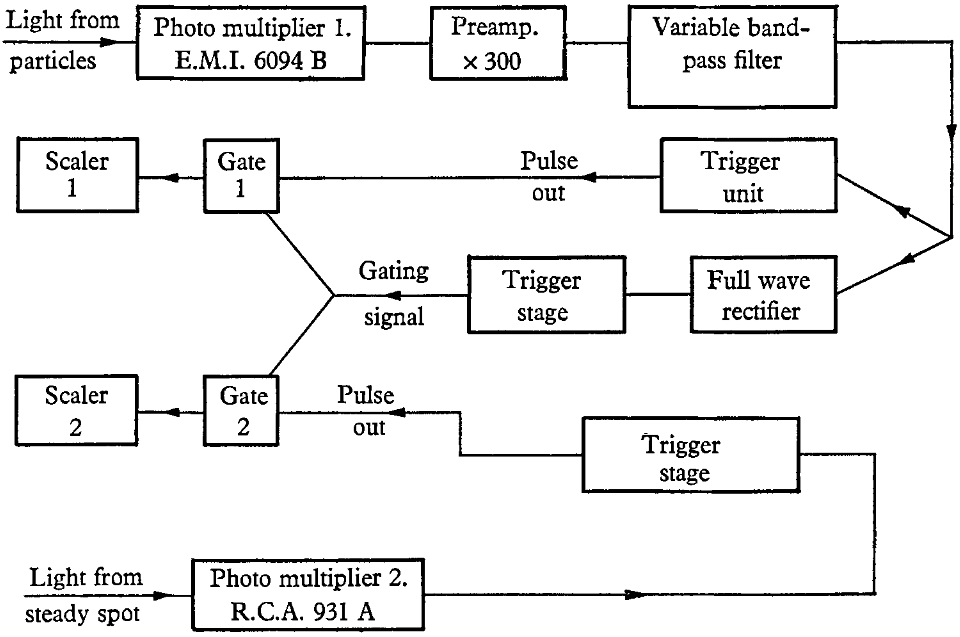


FIGURE 6. Block diagram of electronics.

The filtered photo-multiplier output was also used to control the gating circuits. The signal was full-wave rectified, smoothed by a condenser and then fed to a trigger stage which finally drove the gating valve. To prevent large signals from paralysing this stage by over-charging the smoothing condenser and thus allowing the gate to remain open for a short time after a wave packet had passed, it was necessary to limit the rectified signal before the smoothing stage. It was also found useful to incorporate a certain amount of backlash in this trigger circuit to prevent the gates from rapidly flickering on and off when the signal level was marginal. In the original apparatus the Schmitt circuit was designed to have the necessary backlash, but in more recent circuits controlled backlash has been provided by using two schmitts coupled to a bistable device. With this improved system it is possible to set the levels at which the gates open and close independently.

The mean velocity of particles relative to the grid motion is $M^{-1}(C_1/C_2)\,(f/N)$ ft./sec, where C_1 is the count on scaler 1, C_2 is the count on scaler 2, M is the optical magnification, N is the number of grid lines per foot, and f is the frequency of the standard pulse rate.

In this instrument the standard frequency providing pulses for the determination of the total counting period was obtained from the stationary light spot signal, so that the speed of the grid is f/N and the actual particle speed is

$$\left[\frac{C_1-C_2}{C_2}\right]\frac{f}{MN}\ \text{ft./sec.}$$

5. Results

The values of some of the parameters which control the behaviour of the instrument are not easily determined for optimum performance by simple theoretical reasoning, and tests had to be carried out in order to arrive at satisfactory quantities. For example, the choice of the sampling volume exposed by the mask is not easily made, since for good resolution a small region is required, but for an accurate estimation of the speed of one particle it is necessary to have a large mask area so that the image crosses as many grating lines as possible. Also, a large viewing volume allows more scattered background light to fall on the photo-cell thus lowering the signal to noise ratio of the system. As a compromise a sampling region 0·08 in. high by 0·02 in. wide and 0·02 in. deep was eventually chosen as this gave an adequate signal combined with sufficiently good spatial resolution. The particle concentration did not appear to be at all critical, but to ensure that most of the signals were generated by isolated particles the number of polystyrene beads in the flow was adjusted so that counting only occurred for 10 % of the time. This required a concentration of about 0·01 % of 0·002 in. diameter spheres.

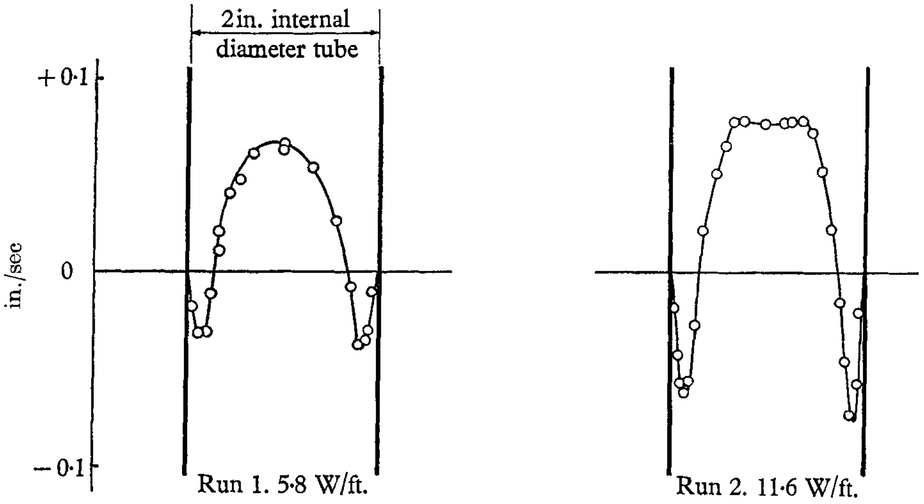


FIGURE 7. Velocity profiles.

The optical magnification of the system and the spacing of the grid lines used on this particular disk gave a frequency deviation of roughly 20 c/s for a particle velocity of 10^{-2} ft./sec, so that a total deviation of −40 to +40 c/s would occur for the required range of velocities. A disk speed giving a carrier frequency of about 200 c/s was found satisfactory, although with re-designed electronics and scalers capable of counting at higher rates, there may be some advantages in using very much higher speeds.

The instrument was used to measure a number of velocity profiles at different input power levels to the cell, two examples being shown in figure 7. These results were obtained over a sampling period of 20 min.

6. Concluding remarks

The results obtained from this instrument, even in its crude initial form, suggest that it is capable of measuring the mean velocities in turbulent flows. With various improvements the range of the device could no doubt be extended to enable measurements to be made in a variety of liquid or gas flows.

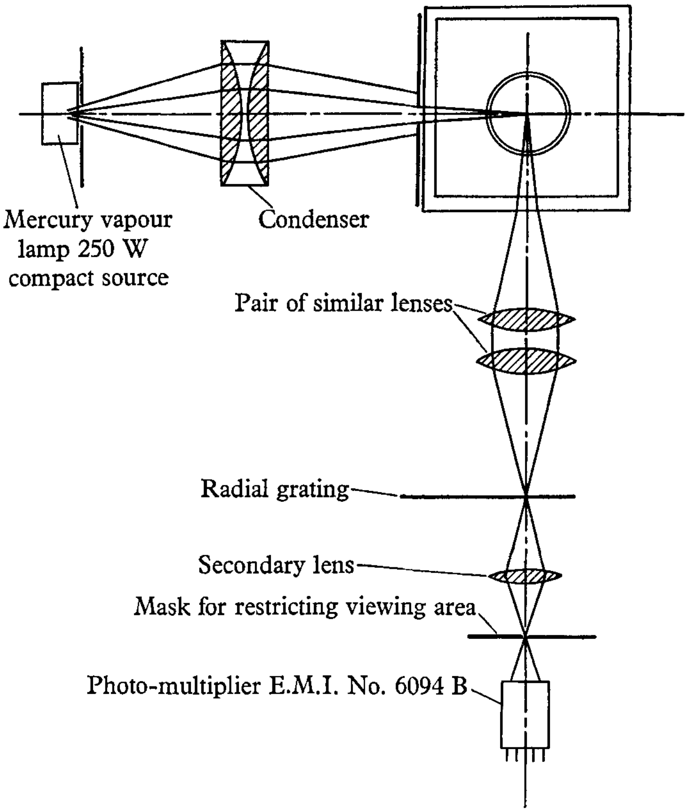
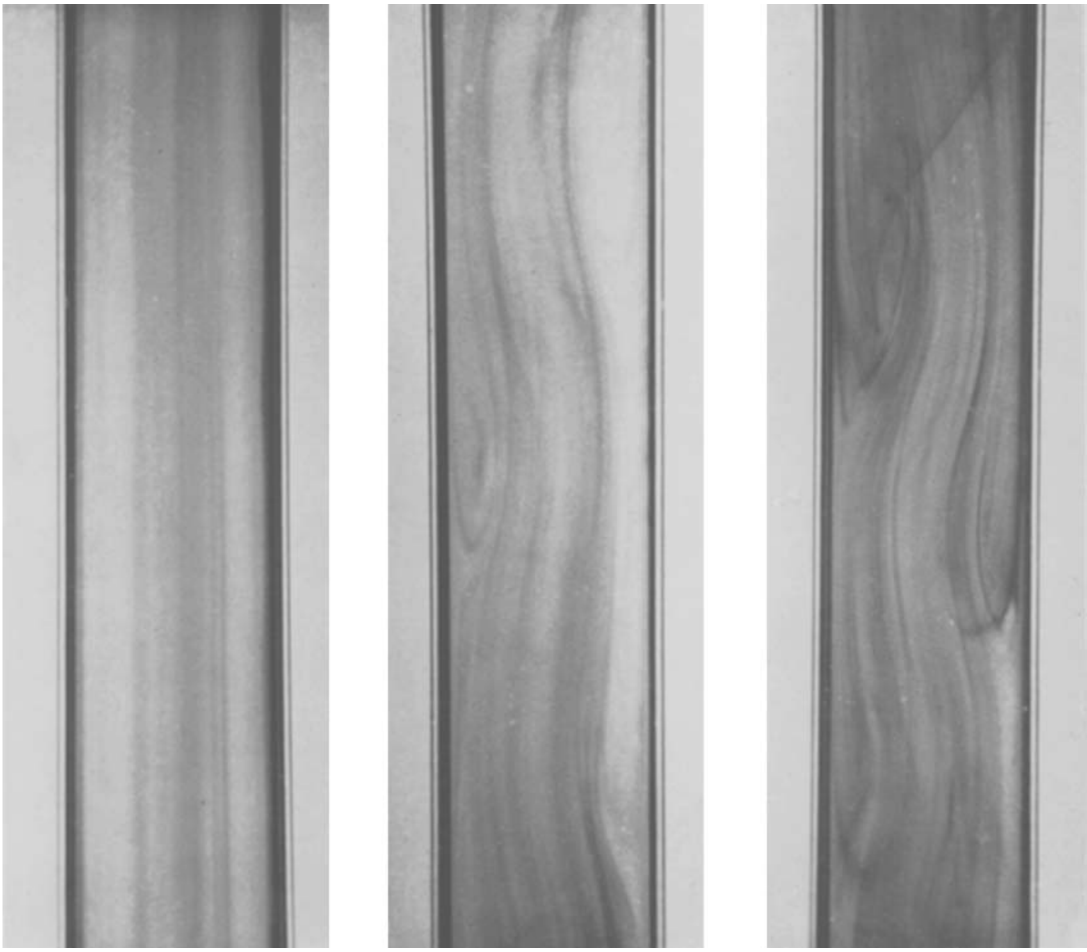


Figure 8. Suggested improved optical layout.

The optical arrangement used was not entirely satisfactory as the particle image falling on the grating could only be made reasonably sharp by stopping down both lenses to $f8$. A much better layout, shown in figure 8, would use a pair of lenses to focus the particle image on the grid and a secondary lens-system would then refocus the transmitted light on the plane of the mask. In this way the lenses work in the best way and the sharp primary image falls directly on the grating. It should be possible, by using large aperture lenses, to increase the signal strength by a significant amount.

Using a suitable type of subtracting counter it is quite feasible to have $(C_2 - C_1)$ displayed directly on a row of dekatron tubes. This counter could be arranged to stop when C_2 reaches some predetermined value and the reading would then be directly proportional to the mean particle velocity.

The author would like to acknowledge the help and encouragement given by Professor W. Murgatroyd in developing this instrument. This work was carried out with the support of the United Kingdom Atomic Energy Authority, Winfrith, and is published by permission of the Director of that Establishment.



near top of cell cell centre cell top

power input 2 W/ft. power input 3 W/ft.

FIGURE 2. Flow instability patterns.

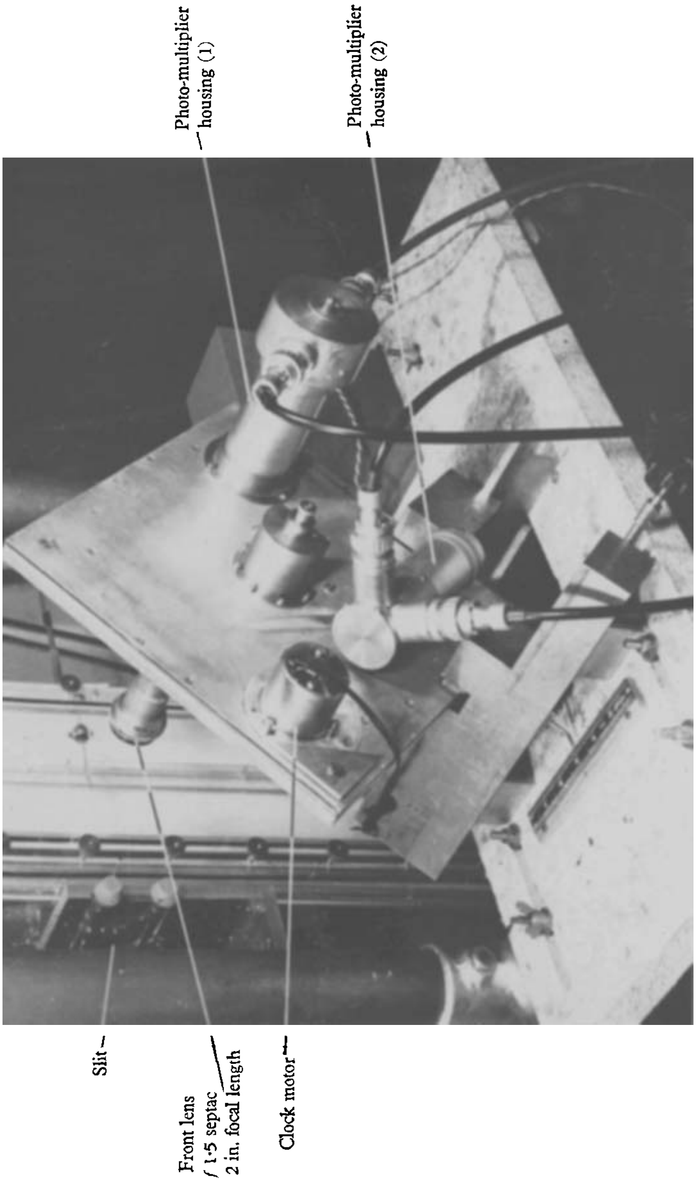


FIGURE 4. The instrument mounted on the rig.

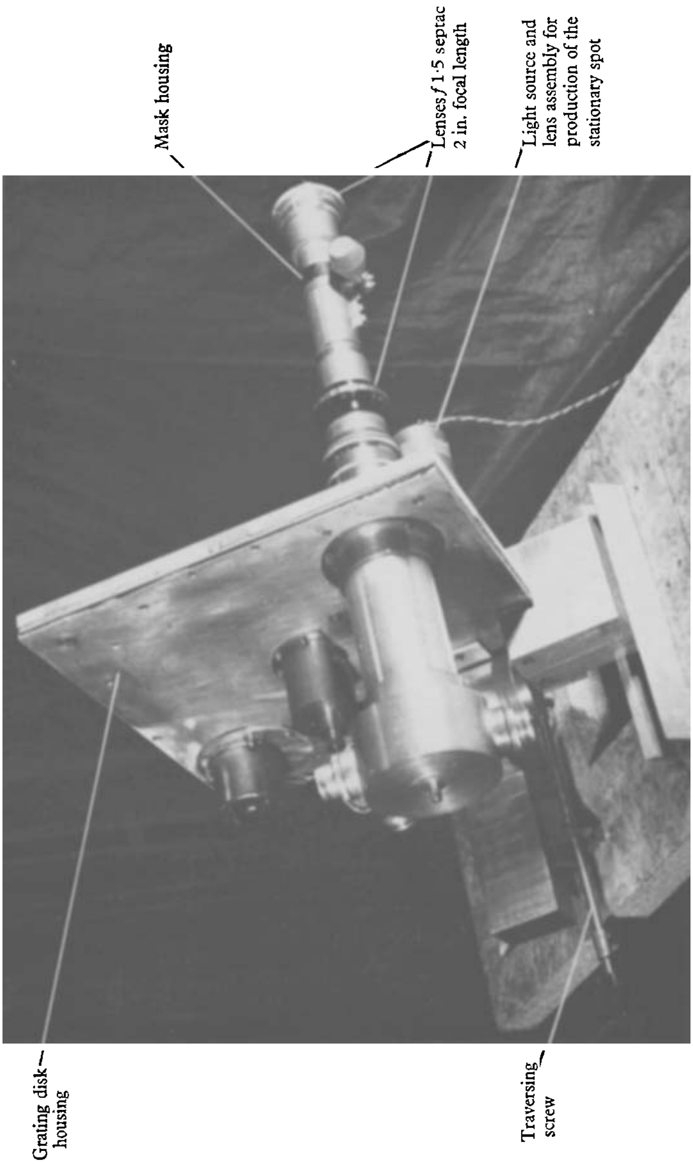


FIGURE 5. Grating assembly.