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Measurement of the growth of a turbulent mercury jet in a coaxial magnetic field

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Using a hot-wire system developed for this purpose, measurements of the velocity were made in a circular liquid-mercury jet issuing into a low-speed secondary flow and subject to a uniform axial magnetic field. The Reynolds number of the jet was about 10,000 while the magnetic interaction parameter varied from zero to slightly over one. The jet was strongly turbulent under all conditions investigated. The radial distribution of the mean and fluctuating component of the meridional velocity was measured at four axial stations located between 2 and 34 diameters from the nozzle exit. The results indicate that the rate of spreading of the jet is decreased, that the shape of the velocity profile changes and that the turbulent intensity decreases with increasing magnetic-field strength. The high-frequency components of the fluctuations in the second flow seem to be damped more strongly than fluctuations at low frequencies, while the reverse is observed within the core of the jet.

1. Introduction

Magnetohydrodynamic turbulence has been the subject of considerable theoretical speculation but little experimentation. Because of the very great difficulty of producing flows on the laboratory scale which possess a very large magnetic Reynolds number, some important questions, such as whether there is equi-partition between the kinetic- and magnetic-energy densities, have not been studied experimentally. Instead, laboratory experiments involving turbulence in MHD flows, at least of incompressible fluids, have been directed mostly toward understanding the gross changes caused by an applied magnetic field in a flow which, in the absence of the field, would be turbulent. For example, the experiments of Murgatroyd (1955) concerning the effect of a transverse magnetic field on a channel flow were of this type. In his experiment the longitudinal pressure gradient was measured, from which inferences concerning the presence and effect of turbulence were drawn.

In laboratory experiments at low magnetic Reynolds number, we distinguish two ways in which a turbulent flow may be affected by an applied magnetic field. The magnetic field may alter the mean flow, as in the experiments of Murgatroyd, and thereby affect the detailed structure of the turbulence through the changes in the mean-vorticity distribution while there may (or may not) be an important

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effect of the magnetic forces on the turbulent eddies themselves. On the other hand, if the mean turbulent flow is essentially parallel to the magnetic field, as in the pipe flow experiments of Globe (1961), the principal effect of the magnetic field will be to change the structure of the turbulence itself, which in turn may affect the mean flow because of a redistribution of turbulent shear stress rather than by direct action of magnetic forces. If the structure of the turbulence can be examined in detail in an experiment of the second kind, then some features of magnetohydrodynamic turbulence (which we define as a turbulent flow in which the fluctuating magnetic force is comparable to the fluctuating inertial force) may be recognizable because the changes in the mean flow are the result of, rather than the cause of, the changed nature of the turbulence.

For a flow of low magnetic Reynolds number which is predominantly parallel to a magnetic field, any component of flow velocity directed normal to a field line is damped out in a characteristic time $\tau \equiv \rho/\sigma B^2$, in which σ is the electrical conductivity and ρ the mass density of the fluid, and B is the magnetic induction of the applied field. If ℓ is the scale and u is the velocity of a turbulent eddy perpendicular to the field in such a flow, then its motion will be rapidly damped if $\tau \ll \ell/u$. In other words, an eddy whose magnetic-interaction parameter $S \equiv \sigma B^2 \ell/\rho u$ (based on the eddy size and velocity) is much greater than unity will be rapidly damped, while those of small interaction parameter will be unaffected during their much shorter lifetimes. Compared with a non-magnetic flow having the same viscous Reynolds number, our *a priori* expectation is that the larger scale components of the turbulence would be missing. To observe any effect, therefore, one requires an interaction parameter, based on the gross scale and velocity of the flow, of the order of unity or greater.

We have chosen to study the structure of a round turbulent jet in a coaxial magnetic field by measuring the mean and fluctuating components of the velocity with a hot wire. From what has been discussed above, it was considered necessary to test under conditions for which the interaction parameter based on nozzle diameter and velocity was of the order of unity. (Since the width of a free jet increases, while its velocity decreases, with distance from the nozzle the 'local' value of the interaction parameter increases in the stream direction.) For a given fluid (mercury in our experiments), the interaction parameter increases with both the scale of the experiment and the magnetic-field intensity. The economy of investment in mercury, field coils, and power supply limited us to a nozzle diameter of about 1 cm and a magnetic intensity of 4 kG. To obtain an interaction parameter of one or greater, it is therefore necessary for the flow velocity not to exceed about 10 cm/sec.

One of us (Sajben 1964, 1965) has developed a hot-wire anemometer capable of measuring velocities in liquid mercury between 0·5 and 12 cm/sec. Using a single hot wire, mean and fluctuating velocity components in one meridional plane were measured. (No spectral analysis of the fluctuating component was made.) These velocity distributions, which give evidence of an alteration of the structure of the jet due to the coaxial magnetic field, are the principle experimental results reported herein.

Because of the limited range of velocity (1–10 cm/sec) for which the hot wire is sensitive, and because its length was to be less than the jet diameter there was available only a small range of viscous Reynolds number Re (about 10^3–10^4, based on nozzle diameter d and velocity V) for which velocity distributions could be measured. The upper limit of magnetic-field strength, about 4 kG, permitted

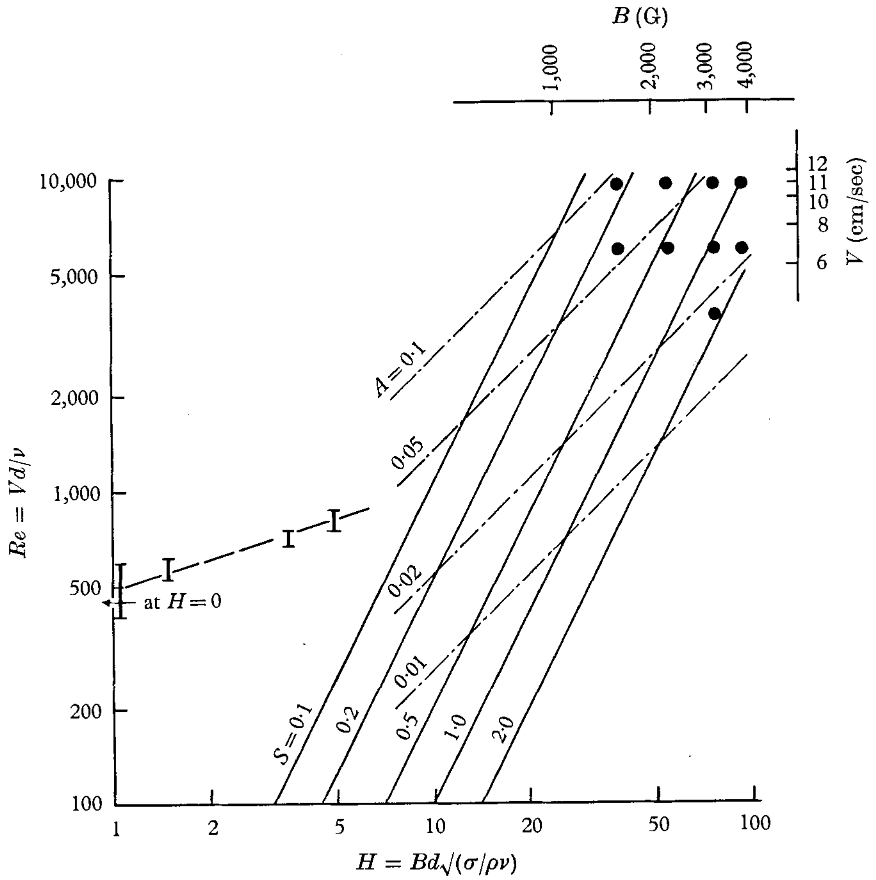

FIGURE 1. The range of Reynolds number Re and Hartmann number H at which measurements were made is shown by the solid circles. Preliminary transition experiments are indicated by vertical bars. Lines of constant interaction parameter S and Alfvén number $A \equiv V\sqrt{(\rho\mu_0/B^2)}$ are shown for reference. For mercury, the magnetic Reynolds number is $1\cdot5 \times 10^{-7} Re$.

a range of Hartmann number $H \equiv Bd\sqrt{(\sigma/\rho\nu)}$ from zero to about 100. In figure 1 we have superposed on a plot of Re versus H the conditions under which experimental data was recorded (solid circles) and, for a jet diameter of 1 cm, give auxiliary scales of velocity and magnetic field strength. For reference, we also show lines of constant interaction parameter $S \equiv H^2/Re$ and Alfvén number $A \equiv V/\sqrt{(B^2/\rho\mu_0)} = Re\sqrt{Pr_m}/H$, where μ_0 is the vacuum magnetic permeability and the magnetic Prandtl number $Pr_m \equiv \mu_0\sigma\nu$ of mercury has the value of $1\cdot5 \times 10^{-7}$. The magnetic Reynolds number Re_m of these experiments is about 10^{-3}.

Since the interest lay primarily in turbulent flow, the boundary between laminar and turbulent regions (transition Reynolds numbers) was of some importance. A simple but quantitative experiment (to be described below) was performed to obtain this information which gave results indicated by the scatter bars on figure 1. Extrapolating the data gave hope that for Hartmann numbers less than 100 and S less than unity, turbulent flow would exist in the test section, as indeed was subsequently observed.

It would be preferable to have had a jet issuing into an infinite fluid, for which the jet (in the absence of a magnetic field) develops in a self-similar way, the jet width growing in proportion to the distance from the nozzle and the centreline velocity decreasing inversely with the same distance. Because of obvious limitations, it was necessary to surround the jet with a coaxial flow. This secondary flow had an outer diameter of 12·8 cm (compared with 0·98 cm diameter of the nozzle) and a low velocity (about 1 cm/sec compared with a nozzle velocity of 10 cm/sec). Under these conditions the secondary stream had a mass flow about ten times that of the primary (jet) flow and a total momentum about equal to that of the jet. Our measurements were made within thirty diameters from the nozzle, a region within which, for a free jet, the mass flow in the jet triples while the momentum remains constant. Our secondary flow therefore provided five times the mass flow required for jet growth while adding only about 20 % to the jet momentum. We had therefore expected that the main features of a free jet would be present in our confined jet, which was subsequently found to be the case when the magnetic field was absent.

Even in an infinite fluid, the magnetic field would affect the flow far from the jet and thereby the rate of entrainment of fluid by the jet. For large Reynolds number laminar flow, Hoult (1965*a*) has shown that the flow in the jet near the source is unaffected by the magnetic field, although it is considerably altered far from the jet centreline. For a turbulent jet, which spreads more rapidly, these effects would be more prominent, but we do not expect that they would dominate the jet flow close to the centreline and not far from the nozzle.

On the basis of the usual mixing-length arguments, it is possible to show that a free jet in a strong coaxial magnetic field would develop in a self-similar manner but according to a different growth law than that of the non-magnetic jet. In order to do so, it is necessary to assume that the mixing length, which gives the order of magnitude of the eddy viscosity ϵ when multiplied by the jet velocity V, is equal to the scale of the largest undamped eddy rather than equal to the jet width δ, as is usually assumed for the non-magnetic case. The magnitude of ϵ therefore becomes $V^2\tau$, which is less than $V\delta$ by assumption. If this value is inserted into the axial momentum equation,

$$\frac{DV}{Dt} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\epsilon\frac{\partial V}{\partial r}\right), \tag{1}$$

in which D/Dt is the convective derivative and r is the radial co-ordinate, then the following order of magnitude equality holds

$$V^2/x \approx V^3\tau/\delta^2, \tag{2}$$

provided that $D/Dt \approx V/x$ and $\partial/\partial r \approx 1/\delta$. If the jet momentum is conserved, then $V \propto \delta^{-1}$ and it follows from (2) that

$$\delta \propto V^{-1} \propto (\tau x)^{\frac{1}{3}} \propto B^{-\frac{2}{3}} x^{\frac{1}{3}}. \qquad (3)$$

This is in contrast to the non-magnetic free jet, for which the assumption of $\epsilon \approx V\delta$ leads to δ and V^{-1} varying as x. The slower rate of growth is a consequence of the assumption of a smaller mixing length and therefore a smaller turbulent viscosity.

In writing equation (1) we have neglected to include the axial-pressure-gradient term, $\rho^{-1}(\partial p/\partial x)$. Because of the gradual spreading of the jet, there will be a radial velocity of order $V\delta/x$ which induces an azimuthal current density of order $\sigma(V\delta/x)B$. The corresponding inwardly directed magnetic force must therefore be balanced by a pressure difference of about $\sigma V\delta^2 B^2/x$ between the centre of the jet and the surrounding fluid. The order of magnitude of the axial-pressure gradient term would thus be $\sigma V\delta^2 B^2/\rho x^2$, or about $\sigma\delta^2 B^2/\rho x V$ times the inertial term DV/Dt. Since $\sigma B^2\delta/\rho V$ is not much greater than unity in our experiments while δ/x is much less than unity, the axial pressure gradient will have little effect upon the jet growth within the axial distance of our experiments.

The damping time $\tau \equiv \rho/\sigma B^2$ correctly estimates the rate at which three-dimensional motion of the fluid is damped by the applied magnetic field. However, motion which is predominantly in a plane normal to the magnetic field is damped more slowly. For example, in studying the stability of an axisymmetric jet Hoult (1965*b*) showed that disturbances of very long wavelenth λ are damped more slowly than those of short wavelength, the damping time being approximately $(\lambda/\delta)^2\tau$ for $\lambda \gg \delta$. The cause of this difference between the two- and three-dimensional disturbances lies in the presence of an electric field $\mathbf{E}$ which reduces the current $\mathbf{j}$ to a value much less than $\sigma\mathbf{V}\times\mathbf{B}$ whenever the motion is nearly two-dimensional. To show how this arises, consider the approximate ohm's law valid for small Rm

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{V} \times B\mathbf{k}), \qquad (4)$$

where $B\mathbf{k}$ is the uniform applied magnetic field, $\mathbf{k}$ being the unit vector in the direction of $\mathbf{B}$. The equation of continuity for two-dimensional flow in the plane normal to $\mathbf{k}$ is satisfied by choosing

$$\mathbf{V} = \nabla \times \psi\mathbf{k} = -\mathbf{k} \times \nabla\psi, \qquad (5)$$

where ψ is a function of position in the normal plane. From (4), no current will flow provided

$$\mathbf{E} = B\nabla\psi, \qquad (6)$$

which is a satisfactory solution to Faraday's law provided the flow is steady or current-free. Thus a two-dimensional flow of a type describable by (5) is undamped by the magnetic field. It is clear from (5) that ψ is the stream function and from (6) that the streamlines are also equipotential lines.

Without discussing the details of such flows, it can be concluded that disturbances having wave vectors predominantly in the transverse plane will not damp rapidly. Such motions, which carry mostly axial vorticity, will probably not be effective in distributing the azimuthal vorticity which is necessary for the spreading of the jet. It is to be expected that the magnetic field can therefore inhibit the spreading of the jet even though it may not damp all motions of wavelength comparable to the jet width.

2. Preliminary transition experiment

A simple experiment was carried out to determine the magnitude of the stabilizing influence of a parallel magnetic field on a free jet. A jet was produced by a hypodermic needle mounted vertically along the axis of a cylindrical pool of mercury, the nozzle tip being submerged below the free surface by about forty diameters. The upwardly directed jet produced a dimple on the surface, which was irregularly trembling at higher flow rates and was perfectly steady at low flows. These states were interpreted as turbulent or stable laminar flows of the jet, and the flow rate corresponding to a transition state was taken to define a transition Reynolds number. A coaxial magnetic field, generated by an open core solenoid, was varied independently of the jet flow rate.

Three sizes of hypodermic needle were used, each long enough to assure a fully developed laminar profile at the nozzle exit in the absence of a magnetic field. The nozzle was fed gravitationally from a graduated burette. As the burette was gradually emptied during the experiment, the diminishing level difference between burette and pool drove a decreasing flow rate through the system, eventually causing a transition from turbulent to laminar flow of the jet. The device was mounted on a vibration-damping platform which filtered out external disturbances having frequencies greater than approximately 1 c/s, so that the experiment tended to display the behaviour of low-frequency random perturbations imposed on the jet. The scatter bars of figure 1 represent the range of results obtained from approximately 60 runs.

The data show a general tendency towards increasing transition Reynolds number for increasing Hartmann numbers, as was expected on the basis of purely qualitative arguments as well as by analogy to existing stability investigations in parallel flow (Stuart 1954; Drazin 1960). Extrapolating this tendency to larger Hartmann numbers gave an indication that turbulent flow would probably be encountered under the planned experimental conditions.

The absolute value of the transition Reynolds number in the absence of magnetic field is large compared to data obtained by others ($Re = 10$ to 300, Andrade & Tsien 1937; Viilu 1962). The reason for the discrepancy may lie in part in the unavoidable contamination layer on top of free mercury surfaces which is very effective in concealing motions within the fluid,* as well as with the effect of a free surface itself.

3. Experimental apparatus

A detailed description of the experimental apparatus and instrumentation having been made available elsewhere (Sajben 1964, 1965), we restrict our discussion to those details which have direct bearing on the structure of the flow pattern under study.

* It could be demonstrated with the aid of a hot wire that considerable velocities can exist immediately beneath an apparently motionless mercury surface (1–2 cm/sec at 1 cm depth).

Figure 2 shows the test section, its more important dimensions being given in millimeters. The primary flow issuing from the 50 cm long tubular nozzle presumably had a fully developed turbulent velocity profile with mean velocities ranging from 3 to 15 cm/sec. The secondary flow, entering through the screen assembly, had a mean speed of one-tenth that of the primary jet. The screen

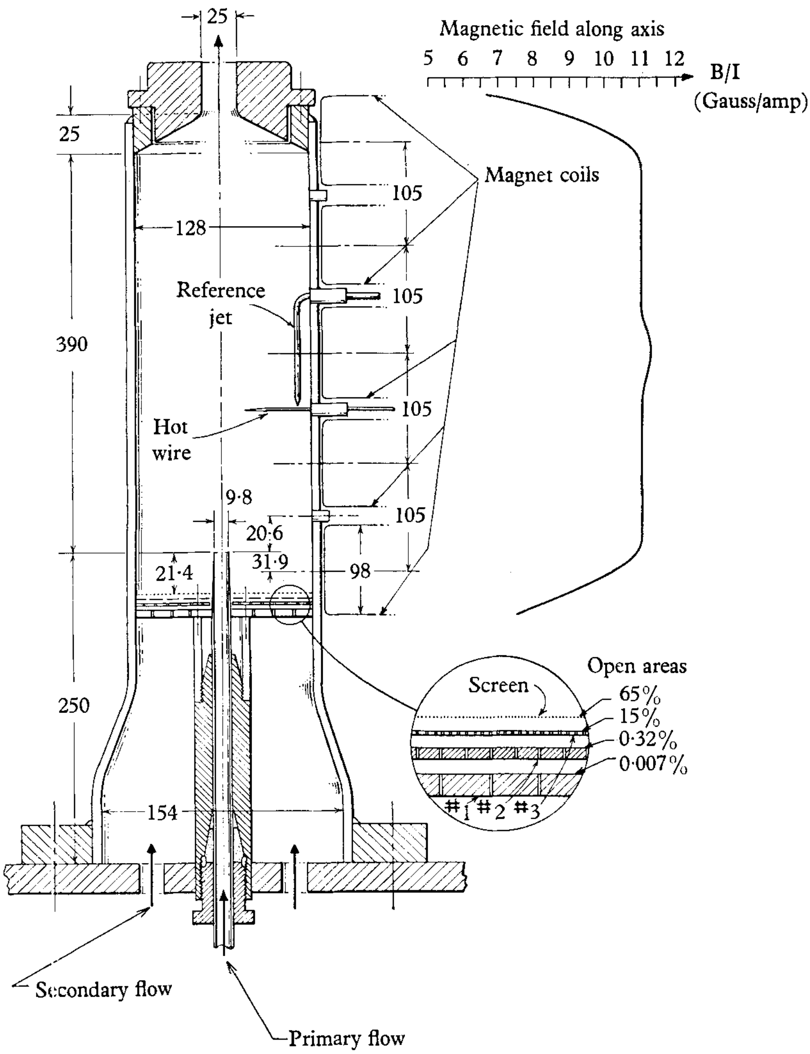

FIGURE 2. A cross-section of the coaxial flow chamber. All dimensions shown are in millimetres.

assembly served the purpose of eliminating the non-uniformities introduced by the fringing magnetic field. The high cost of uniform magnetic field necessitated an unorthodox screen design with small axial dimensions, which did provide the desired uniform velocity distribution, although at the expense of rather high background turbulent intensity, as we shall see shortly.

Four test ports were provided at distances of 2·1, 12·8, 23·1 and 34·2 diameters away from the nozzle exit, all in the same meridional plane. The hot-wire sensor could be traversed from wall to wall at each station. The 'reference jet' shown was used to obtain calibrations at a fixed reference speed between test runs, required to compensate for a slow drift in the hot-wire signal.

The test section was surrounded by five magnet coils stacked vertically, providing a nearly uniform field intensity between the centres of the end coils when a suitable non-uniform current distribution was supplied. The variation of the field in time, introduced by the rectifier power source, was about 0·01 %, which is more than one order of magnitude less than the expected intensity of turbulent magnetic-field fluctuations. The available power limited the maximum field strength to 4 kG.

The sensitive element of the anemometer is a tungsten wire of 38 μ diameter and 5 mm length, covered with an enamel coat of 2·5 μ thickness. The wire was operated in a constant-current mode, and a non-linear amplifier was used to give an output proportional to velocity with a flat frequency response up to 1 kc/sec, which was ample for our experiments. Considerable difficulty was encountered in maintaining a constant calibration because of the accumulation of impurities in the mercury on the surface of the hot wire. This and other difficulties which have made the accuracy and reproducibility of the measurements less than is customary in hot-wire experiments are discussed in greater detail by Sajben (1964, 1965).

4. Experimental results and discussion

In first approximation, the data taken correspond to mean velocities and to the root-mean-square values of the streamwise fluctuating-velocity component. More precisely defined, the quantities measured are: (*a*) the time average of the quantity $\sqrt{\{(\tilde{U}+u)^2+(\tilde{V}+v)^2\}}$, and (*b*) the root-mean-square value of the fluctuating component of the same quantity, denoted by $\overline{V}$ and $\sqrt{\{\overline{(V-\overline{V})^2}\}}$, respectively. Here $\tilde{U}$, $\tilde{V}$ represent the radial and axial components of the mean velocity and u, v are the fluctuating-velocity components in the same directions. It is not possible to define these components (their RMS values) in terms of the two measured average quantities and the approximate identification stated above holds for small fluctuations only. However, for the purposes of comparison between the behaviour of the same jet with and without magnetic field, it is not really necessary to break down the results into perpendicular components, since the fundamental changes are readily discernible directly from the measured quantities.

The mean-velocity profiles for the first three stations are shown in figures 3–5. In figure 4 we indicated the test points taken at zero magnetic field only, while runs made with non-zero magnetic fields are represented by smoothed curves to preserve the clarity of the display.* The scatter in other runs was usually less than the scatter shown for $S = 0$. Except where otherwise stated, the Reynolds number based on mean primary velocity and nozzle diameter was kept constant at a value of 9550.

At all axial positions, the principal effect of an increasing magnetic field is to increase the centreline velocity $\overline{V}_m$, the jet width decreasing in order to conserve

* Sajben (1964) contains all data points.

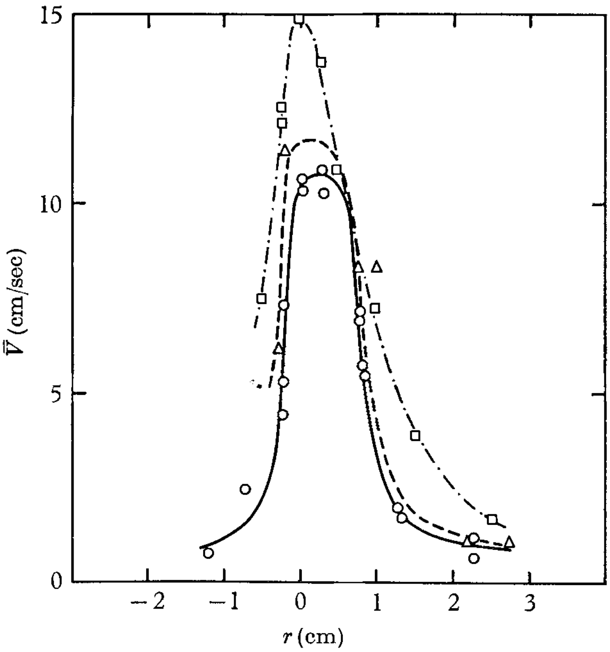

FIGURE 3. Radial distribution of mean velocity at $x/d = 2{\cdot}1$. ○, ——, $S = 0$; △, – – –, $S = 0{\cdot}424$, □, —·—, $S = 0{\cdot}853$.

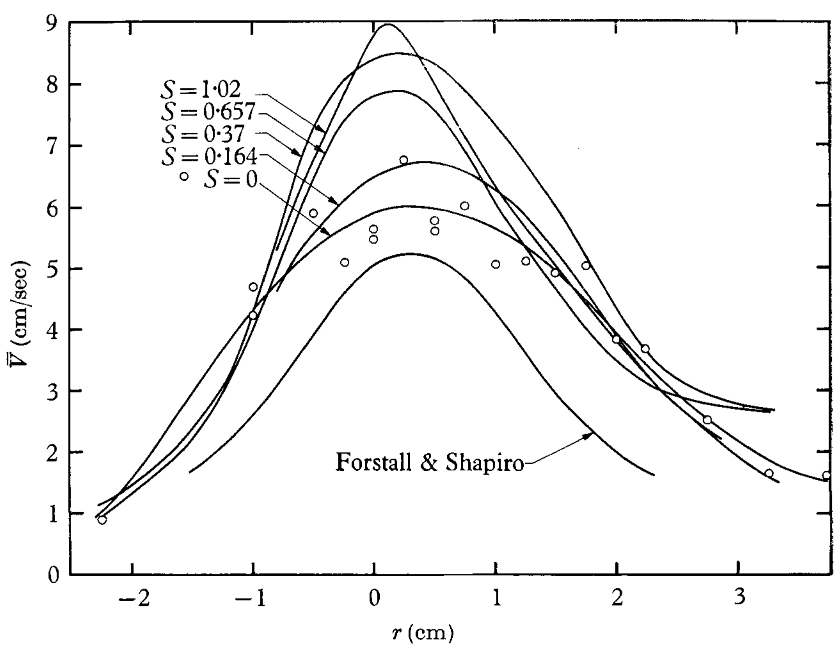

FIGURE 4. Radial distribution of mean velocity at $x/d = 12{\cdot}8$. Experimental measurements are shown for $S = 0$, other curves having been faired through the measured data. Comparison with measurements of Forstall & Shapiro is also shown.

axial momentum. For a value of S of about unity, the centreline velocity has increased approximately 50 % above its non-magnetic value at all axial positions. In figures 4 and 5 we compare our non-magnetic ($S = 0$) velocity profiles with those of Forstall & Shapiro (1950) for a coaxial flow, noting poor agreement (figure 4) at $x/d = 12{\cdot}8$, which we discuss further below. Despite the scatter in the data, the less rapid growth of the magnetic jet compared with the non-magnet case is clearly evident.

Figure 3 shows that the sharply peaked 'magnetic' profiles appear very close to the nozzle mouth ($x/d = 2{\cdot}1$), at a location where the profile should be similar

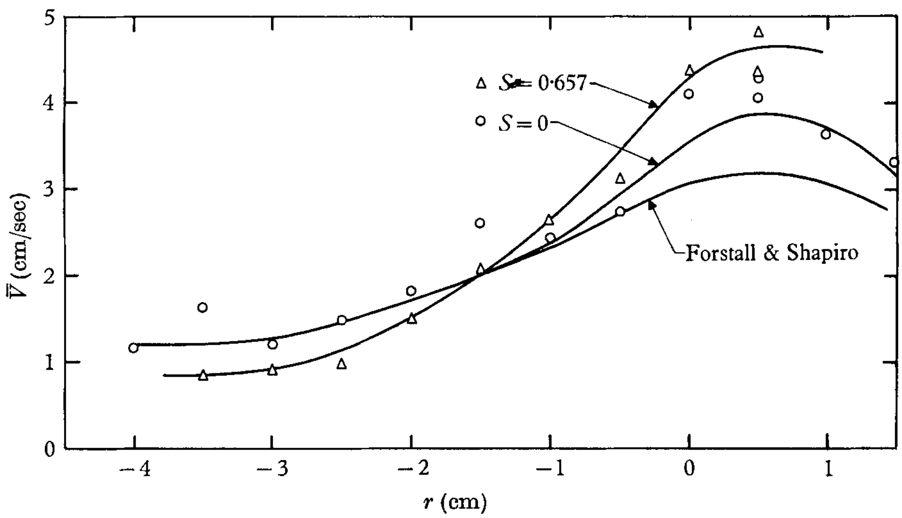

FIGURE 5. Radial distribution of mean velocity at $x/d = 23{\cdot}1$, also compared with measurement of Forstall & Shapiro.

to that within the nozzle. This implies that the sharpness of the initial velocity distribution either originates in the fringing magnetic field through which the nozzle flow must pass or is characteristic of pipe flow in a coaxial field. In the absence of a magnetic field, any irregularities which are caused by entrance effects disappear within several diameters from the nozzle exit. We therefore do not think that entrance effects alone can be the cause of the change in velocity profile observed at $x/d = 12{\cdot}8$ and $23{\cdot}1$ as seen in figures 4 and 5.

In figures 3–5 it can be seen that the axis of symmetry of the velocity profile and the axis of the test channel ($r = 0$) fail to coincide within several millimetres. Whether this discrepancy was a result of an asymmetry of the flow caused by the presence of the probe, or a slight misalignment of the jet was not determined. We do not consider this discrepancy to be significant.

Two shortcomings of the test channel must be mentioned. The unusual screen design produced a level of turbulence in the secondary flow which was higher than customary in free-jet experiments and which therefore may have affected the rate of spread of the jet. The second deficiency was created by the shape of the outlet section (see figure 2) in which the secondary flow was forced to move radially inward across the magnetic field lines, which could only be accomplished by a reduction in pressure to overcome the magnetic 'drag'. At maximum field strength, this pressure drop was estimated to be somewhat larger than the dynamic head of the jet, and must therefore have affected the velocity distribution in the jet near the exit. The measurements at the last station ($x/d = 34{\cdot}2$) were less precise than those closer to the nozzle because of the decay of jet velocity to a value closer to the secondary flow velocity and because of the level

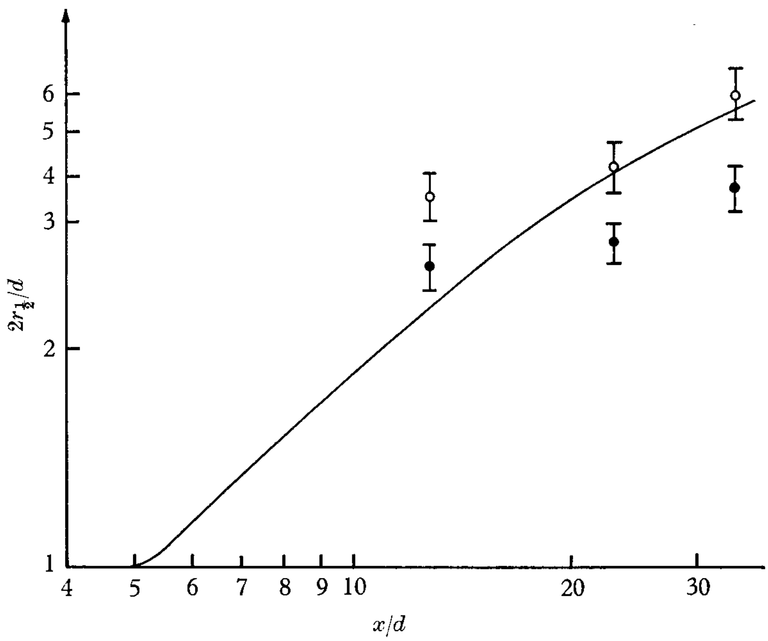

FIGURE 6. Jet half-width as a function of axial distance. ○, $S = 0$; ●, $S = 0{\cdot}657$; —, Forstall & Shapiro.

of turbulence in the secondary flow. Although these measurements close to the exit were somewhat uncertain, no gross effects clearly ascribable to the exit section could be discerned.

The jet half-width $r_{\frac{1}{2}}$, defined as the radius at which the velocity excess $\overline{V} - V_s$ above the secondary flow speed V_s has reached one-half its value on the jet centreline $\overline{V}_m - V_s$ is shown in figure 6 as a function of axial position x/d and interaction parameter S. For the non-magnetic jet ($S = 0$) we notice an anomalously wide jet at $x/d = 12{\cdot}8$ when our results are compared with those of Forstall & Shapiro (1950). We do not understand the reason for this discrepancy, but believe it is probably due to a pattern of recirculation in the secondary flow which is related to those observed by Courtet & Barchilon (1964). Whatever its cause, it signifies an excess of jet momentum above that which exists at other axial locations.

The velocity excess $\overline{V}_m - V_s$ on the centreline is shown in figure 7 as a function of axial position and magnetic-field strength. For the non-magnetic jet it is again compared with the measurements of Forstall & Shapiro (1950). The effect of magnetic field on centreline velocity is greater than that on the jet half-width, but in either case the effect is clearly discernible.

Our previous remarks concerning the growth rate of a magnetized free jet led to the conclusion that the jet width and centreline velocity should vary as $x^{\frac{1}{3}}$ and $x^{-\frac{1}{3}}$ respectively. There is perhaps some indication of this in figures 6 and 7, but the results are undoubtedly affected by the anomalous behaviour at $x/d = 12{\cdot}8$ as well as the fact that our jet is a confined one.

The results shown in figures 6 and 7 are for $S = 0$ or $0{\cdot}66$. Centreline-velocity measurements made at other values of S are shown in figure 8, where each has

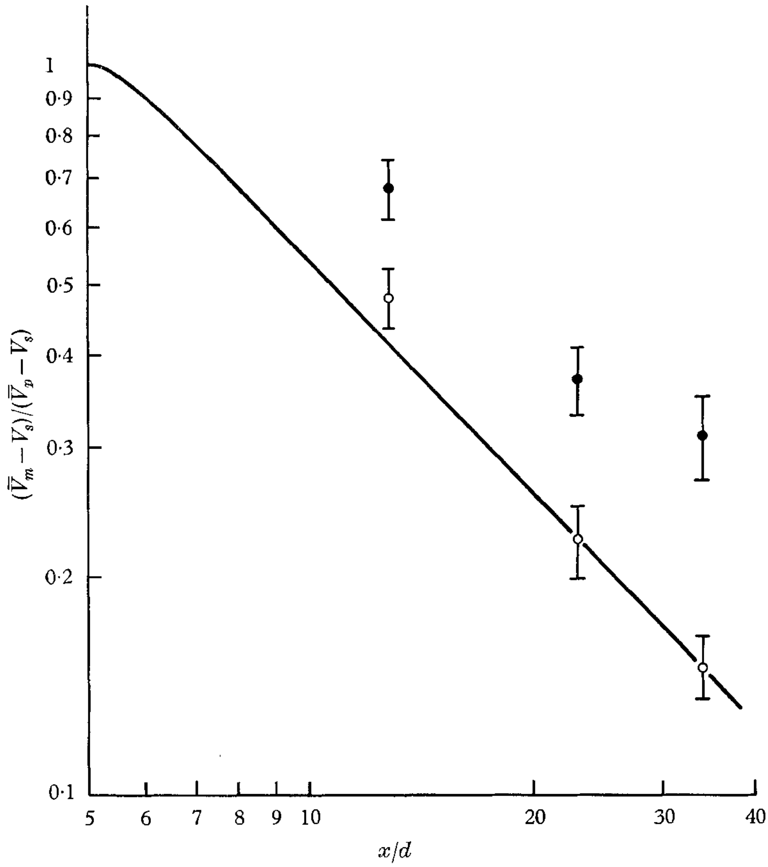

FIGURE 7. Excess of centreline velocity $\overline{V}_m$ above the secondary-flow speed V_s, as a function of axial distance. $\overline{V}_p$ is the value of V_m at the jet exit. ○, $S = 0$; ●, $S = 0{\cdot}66$; —, Forstall & Shapiro.

been normalized with respect to the value at $S = 0$. For the free jet with strong magnetic field, our previous analysis suggested that, at a given axial position, $\overline{V}_m$ should vary as $B^{\frac{2}{3}}$ or $S^{\frac{1}{3}}$. There is some indication in figure 8 that this variation is observed.

Typical distributions of turbulent velocity fluctuations are shown in figure 9 and the corresponding turbulent intensities in figure 10, both for the axial location $x/d = 12{\cdot}8$. There is a considerable decrease in turbulent intensity near the axis when a magnetic field is applied, but this effect is not so noticeable in the region of highest mean shear nor in the region of secondary flow outside the jet. The

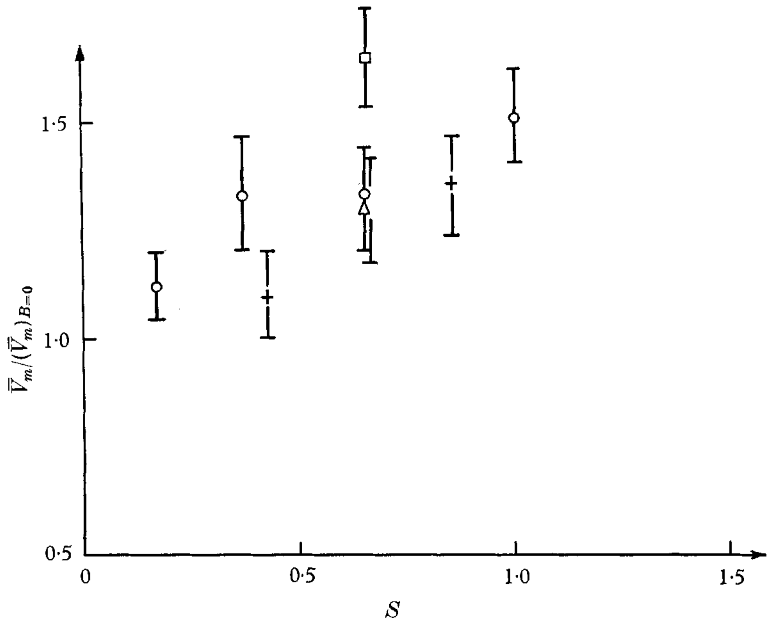

FIGURE 8. Variation of centreline velocity $\overline{V}_m$ with interaction parameter, normalized with respect to the local non-magnetic value. Values of x/d: +, 2·1; ○, 12·8; △, 23·1; □, 34·2.

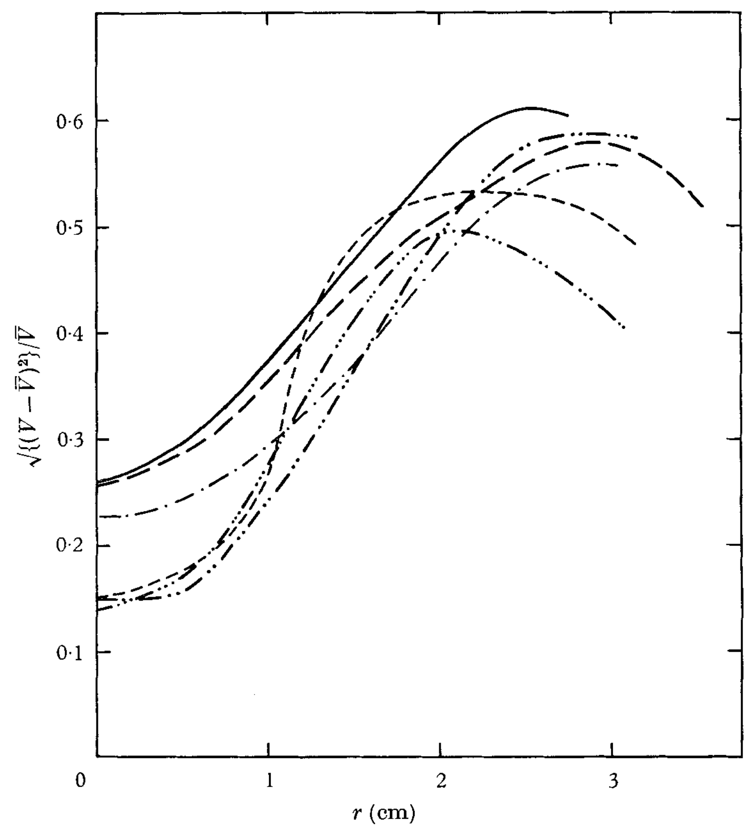

FIGURE 9. Radial distribution of turbulent velocity fluctuations at $x/d = 12·8$. —, Corrsin; – – –, $S = 0$; —·—, $S = 0·164$; —··—, $S = 0·37$; —···—, $S = 0·657$; – – –, $S = 1·02$.

variation of centreline-turbulence intensity with interaction parameter S is shown in figure 11, revealing the rather rapid decrease for even small interaction parameters.

For the purposes of comparison with our measurements at $S = 0$, the turbulent velocity and intensity distributions measured by Courtet & Ricou (1964) in a confined jet having a different ratio of secondary to primary flow than our jet,

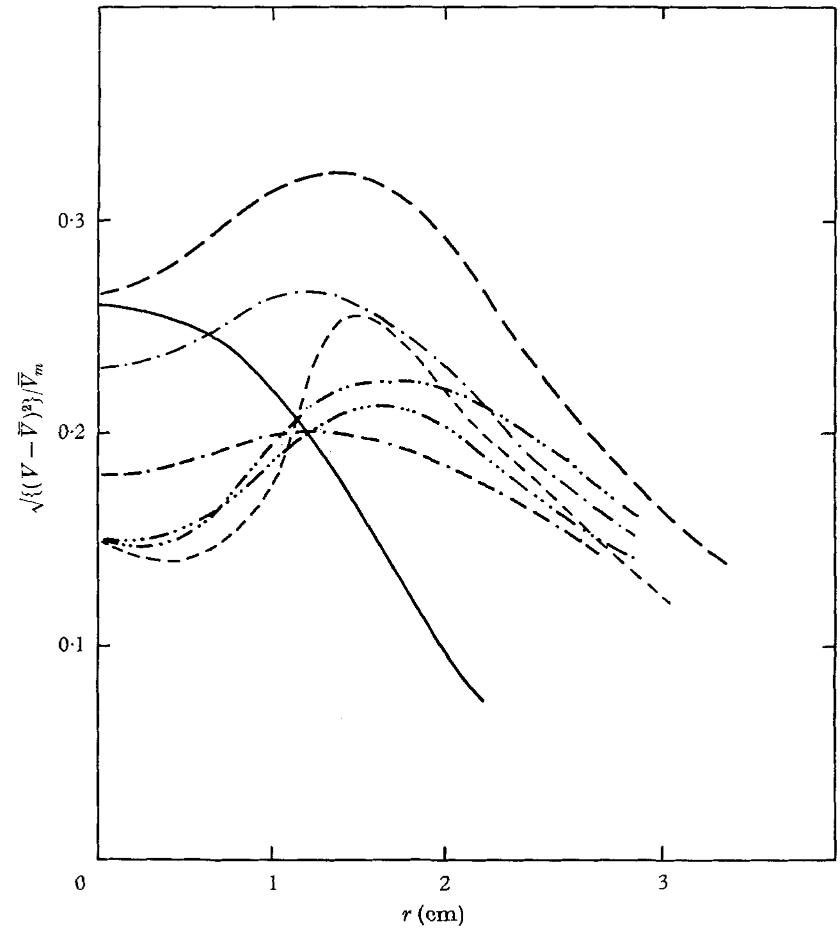

FIGURE 10. Radial distribution of turbulent intensity at $x/d = 12{\cdot}8$. —, Corrsin; ·——·, Courtet; —— $S = 0$; —·—, $S = 0{\cdot}164$; —··—, $S = 0{\cdot}37$; —···—, $S = 0{\cdot}657$; ---, $S = 1{\cdot}02$.

and measurements by Corrsin (1943) in a free jet are also shown in figures 9 and 10. The higher level of turbulence in the secondary flow of the confined jet is a distinct difference from the free-jet distributions, and appears to be typical of usual confined-jet experiments.

Although we have not obtained the frequency spectrum of the turbulence within the jet, there is some indication that the reduction in intensity on the jet centreline caused by the magnetic field is accomplished by dampening the motion of lower frequency more than that of higher frequency. This is the

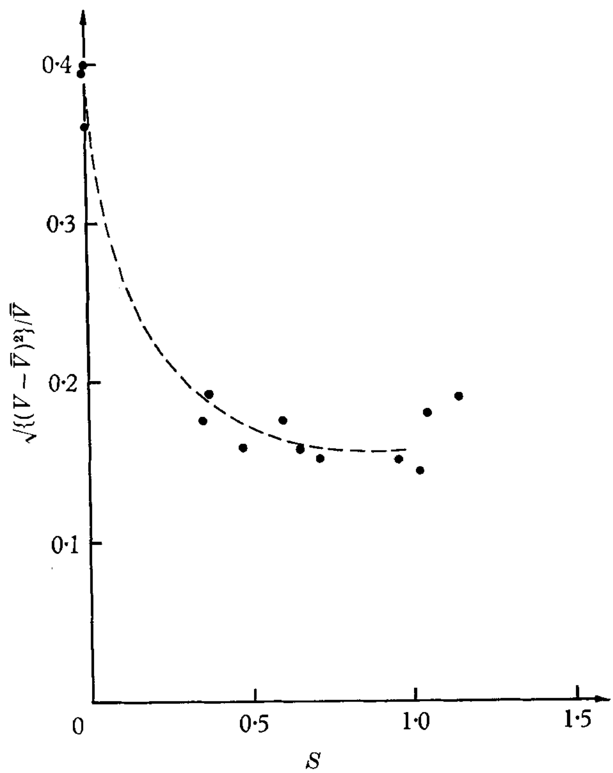

FIGURE 11. Variation of centreline turbulence intensity as a function of interaction parameter S at $x/d = 12{\cdot}8$ and $Re = 6850$.

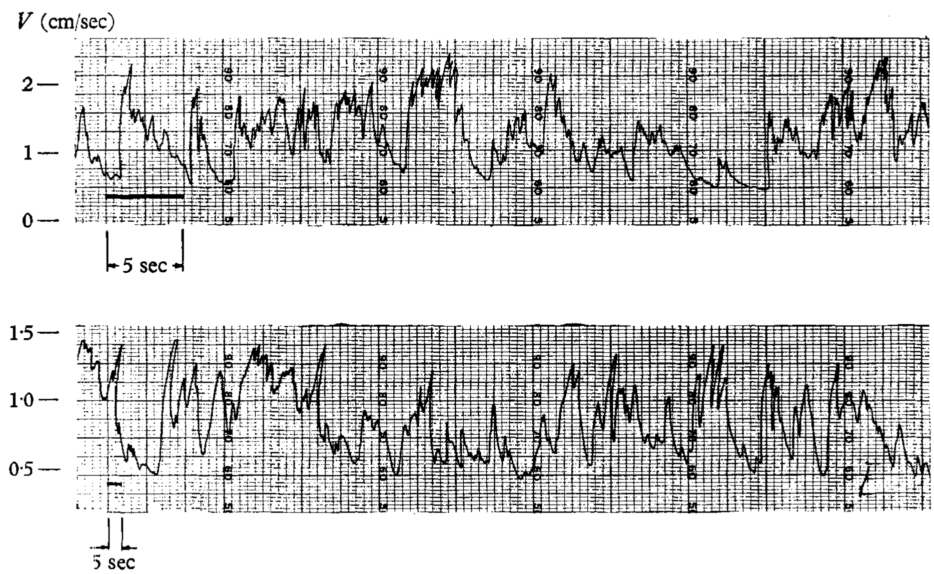

FIGURE 12. Velocity fluctuations in the secondary flow at $x/d = 23{\cdot}1$, $r/d = 9{\cdot}3$ for no magnetic field (upper trace) and $S = 0{\cdot}66$ (lower trace), showing damping of high-frequency components. Notice difference in time scales.

behaviour we had expected *a priori*, with the reservations mentioned in the introduction concerning the possible persistence of predominantly transverse motion. However, the principal effect of the magnetic field is the reduction in turbulence intensity, as shown in figure 10.

The effect of the magnetic field on the secondary flow is shown in figure 12, from which it can be seen that the high-frequency disturbances are damped, the low-frequency components remaining unaffected. This paradoxical behaviour, which is opposite to that observed within the jet, can be explained if it is assumed that disturbances originating within the jet and having wavelengths much longer than the jet diameter are only slightly damped for the reasons discussed in the introduction. Thus wavelengths greater than 10 cm, having frequencies therefore less than about 1 c/s, for the conditions of figure 12, might persist undamped in the secondary flow. This frequency is approximately the high-frequency cutoff of the lower trace of figure 12.

5. Conclusions

Measurements of mean velocity and turbulent intensity in a round confined jet of liquid mercury were made. The experiment demonstrated that the superposition of a uniform parallel magnetic field results in several major changes in the nature of the flow. The field (*a*) reduces the turbulent momentum transfer perpendicular to the field, which results in a reduced rate of growth in the axial direction; (*b*) reduces the turbulent intensity, especially on the axis where the mean-velocity gradients are small; and (*c*) at sufficiently high values of the interaction parameter it damps out the low-frequency components of the turbulent motion in the jet and the high-frequency components in the secondary flow. All these effects may be qualitatively understood in terms of magnetic damping and magnetic mixing length.

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REFERENCES

Andrade, E. N. & Tsien, L. D. 1937 *Proc. Phys. Soc.* **49**, 381.
Corrsin, S. 1943 *NACA Wartime Rep.* no. W-94.
Courtet, R. & Barchilon, M. 1964 *ASME Paper*, no. 64-FE-23.
Courtet, R. & Ricou, F. P. 1964 *ASME Paper*, no. 64-FE-20.
Drazin, P. G. 1960 *J. Fluid Mech.* **8**, 130.
Forstall, W. & Shapiro, A. H. 1950 *J. Appl. Mech.* **7**, 399.
Globe, S. 1961 *J. Heat transfer*, **83**, 445.
Hoult, D. P. 1965*a* *Phys. Fluids*, **8**, 886.
Hoult, D. P. 1965*b* *Phys. Fluids*, **8**, 1456.
Murgatroyd, W. 1955 *Phil. Mag.* **44**, 1348.
Sajben, M. 1964 Sc.D. Thesis. Massachusetts Institute of Technology.
Sajben, M. 1965 *Rev. Scient. Instrum.* **36**, 945.
Stuart, J. T. 1954 *Proc. Roy. Soc.* A **223**, 105.
Viilu, A. 1962 *J. Appl. Mech.* **29**, 506.