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TURBULENCE MEASUREMENTS WITH HOT-WIRE ANEMOMETRY IN NON-HOMOGENEOUS JETS*

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Abstract—The axial distributions of some turbulence quantities in round jets discharging into quiescent air have been measured. The primary purpose of the investigation was to establish the validity of a measurement technique using hot-wire anemometry previously described by the authors. The distribution of the intensity of axial velocity fluctuations has been measured in a jet of carbon dioxide, and the distributions of the covariance of axial velocity and concentration fluctuations, and of the intensity of concentration fluctuations, have been measured in a jet of argon. The measurements are compared with those made by Way and Libby and by Becker, Hottel and Williams, each using alternative techniques, and good agreement is found with the measurements reported by Way and Libby.

NOMENCLATURE

A,	intercept of hot-wire calibration;
B,	slope of hot-wire calibration;
d,	nozzle diameter;
n,	index in hot-wire response equation,
R,	Reynolds number based on nozzle diameter;
$R_{u\gamma}$,	correlation coefficient;
u,	fluctuation in x-direction velocity about mean;
U,	instantaneous velocity in x-direction;
v,	fluctuation in wire voltage about mean *or* fluctuation in transverse velocity component about mean;
V,	instantaneous wire voltage;
x,	axial distance from nozzle exit.

Greek symbols

γ,	fluctuation in concentration about mean;
Γ,	instantaneous molal concentration of second component in mixture;
δ,	sensitivity to velocity fluctuations;
μ,	sensitivity to concentration fluctuations;
ρ,	density;
ϕ,	function of concentration;
ψ,	function of concentration.

Subscripts

m,	refers to mixture of components 1 and 2;
0,	conditions at nozzle exit;
1,	first component (air);
2,	second component;
∞,	conditions in the ambient surroundings.

An overbar indicates a time-mean quantity.

1. INTRODUCTION

In a previous paper [1] we described a procedure for the measurement of turbulence in flows of gas mixtures using hot-wire anemometry. In this paper we describe the application of the technique to turbulence measurements in a round, turbulent, non-homogeneous jet. This was not intended to form a comprehensive investigation of the structure of a non-homogeneous jet. The choice of a jet flow was dictated by the existence of measurements made under these conditions by Way and Libby [2] and by Becker, Hottel and Williams [3]. Corrsin [4] and Corrsin and Uberoi [5] had previously applied hot-wire anemometry to the measurement of velocity and temperature fluctuations in a heated jet of air. They noted that the choice of a jet flow provided a severe test of such an extended use of the hot wire and that measurements in other flow situations—e.g. boundary layers or pipe flows—would undoubtedly be simpler and more reliable. This is true also of the present application of hot-wire anemometry. The range of measurements undertaken here has therefore been limited to those needed to test the validity of the measurement technique. In particular, only measurements of the distributions of some of the turbulence quantities along the axis of the jet are reported.

In their investigation, Way and Libby [2] used a double hot-wire probe, with the two wires at right angles to each other and positioned normal to the direction of the mean stream. The wires were close together so that one wire thermally interfered with the other. Way and Libby found that with this arrangement the voltages across the respective wires combine to provide very good discrimination between the velocity and concentration, whereas with wires which do not thermally interfere with each other it was difficult to distinguish voltage pairs corresponding to high velocity and low concentration from those corresponding to a lower velocity and higher concentration. Way and Libby attributed this latter difficulty to thermal-slip effects with helium, the secondary gas they used in their programme. The discrimination they obtain is indeed better than that obtainable with the procedure reported here; but the Way and Libby technique requires recording and analogue-to-digital conversion equipment which may not readily be available to many experimenters. We have concentrated on attempting to measure turbulence quantities involving the fluctuating concentration, with only conventional analogue hot-wire equipment such as is standard equipment in present-day laboratories. Knowledge of these quantities is of importance in the study of turbulent transfer processes, and their measurement is in principle possible with the hot-wire anemometer. It is thus of some practical importance that the capability of this well-established tool should be extended in this way.

Becker, Hottel and Williams [3] used a light-scattering technique to measure concentration fluctuations in an air jet marked with an oil smoke. This method does not appear to lend itself readily to the measurement of covariances of the fluctuating concentration and velocity components. It also requires equipment not usually available to experimenters.

In [1] it was shown that, for a hot wire with a calibration given by $V^2 = A + BU^n$, the sensitivity of the wire to concentration fluctuations μ is given by

$$\mu = \phi(\bar{\Gamma})\frac{\bar{V}_2^2 - \bar{V}_1^2}{2\bar{V}} \tag{1}$$

where $\phi(\bar{\Gamma})$ is independent of velocity and wire geometry but depends on the secondary gas and the wire overheat ratio (defined as the ratio of wire and gas temperatures). μ is defined by the relation

$$v = \delta\frac{u}{\bar{U}} + \mu\frac{\gamma}{\bar{\Gamma}} \tag{2}$$

where δ is the sensitivity to velocity fluctuations given by $\delta = [n(\bar{V}^2 - A_m)/2\bar{V}]$. In experiments reported in [1], the function $\phi(\bar{\Gamma})$ was measured for air/argon mixtures at overheat ratios of 1·3, 1·8 and 2·5 and was found to be fairly insensitive to overheat ratio. Once $\phi(\bar{\Gamma})$ is known the sensitivities δ and μ at any values of the mean concentration and mean velocity can be determined from the wire calibration in the pure components alone.

In the experiments to be reported, the effect of density difference on the intensity of axial velocity fluctuations is first determined using a simple procedure given in [1], which is applicable to flows of air/carbon dioxide mixtures. The distributions along the jet axis of the intensity of concentration fluctuations and of the covariance of the concentration and velocity fluctuations are then determined in an argon jet.

2. EXPERIMENTAL ARRANGEMENT

The apparatus used consisted of a 1·27 cm dia nozzle preceded by a smooth contraction from a 15 cm dia, 1 m long settling chamber incorporating a honeycomb flow straightener. The mean velocity and concentration distributions in the jet were rectangular at the nozzle exit. The hot wires used were etched Wollaston wire 2·5 μm and 10 μm in diameter with active lengths of 0·8 mm and 2 mm respectively. The hot wires were operated in the constant-temperature mode. The hot-wire signals were not linearized; indeed linearization by analogue methods cannot readily be applied in the situation considered here. (The effect of this is discussed later.) All the measurements were made on the axis of the jet between five and twenty nozzle diameters from the exit plane of the nozzle.

Jets of three different gases discharging into ambient air have been studied in this investigation—air, carbon dioxide and argon. In all cases the jet Reynolds number was $1{\cdot}0 \times 10^4$ and the ambient fluid velocity was zero. The mean concentration in the carbon dioxide jet were measured with an infra-red gas analyser. For the argon jet, the concentrations were measured with a hot-wire anemometer making use of the relationship

$$\psi(\bar{\Gamma}) = \frac{\bar{V}^2 - \bar{V}_1^2}{\bar{V}_2^2 - \bar{V}_1^2} \tag{3}$$

established for air/argon mixtures in [1].

3. MEASUREMENTS OF MEAN QUANTITIES

As a preliminary to the main experiments, the distribution of the mean velocity and mean concentration on the jet axis were measured and compared with established results. For the mean velocity in the air jet, it was found that

$$\frac{\overline{U}_0}{\overline{U}} = 0{\cdot}154\frac{x}{d} + 0{\cdot}10 \tag{4}$$

in good agreement with results of Hinze and Van der Hegge Zijnen [6], as quoted by Hinze [7]. For the argon jet, the effect of the jet fluid/ambient fluid density difference on the velocity distribution was found to be small. This is in agreement with the results reported by Corrsin and Uberoi for a heated air jet at 170° for which the density difference is of comparable magnitude to that for the argon jet.

For both the argon and the carbon dioxide jets, the axial distribution of concentration was found to be

$$\frac{\overline{\Gamma}_0}{\overline{\Gamma}} = 0{\cdot}195\frac{x}{d} + 0{\cdot}01.$$

Becker *et al.*, citing the work of different investigators, quote values of the slope ranging from 0·172 to 0·278 for the case of zero or small density difference. Examination of the results of Keagy and Weller [8] for both nitrogen and carbon dioxide jets shows that the concentration distributions are little affected by the density differences appropriate to these gases, at least for distances from the nozzle up to 20d, and their results are in good agreement with the above expression. Certainly any difference due to density is small relative to the spread of results, presumably due to experimental errors and differences in jet configuration, quoted by Becker *et al.* for jets with nominally zero density difference. It is well known that comparisons of results for round jets are affected by Reynolds number, by differences in nozzle design and by the disposition of the nozzle mounting relative to the local surroundings. Thus the above comparisons for the mean flow are quite acceptable given the admittedly wide range of previously reported results. That such remarks can be applied to the mean flow field, where experimental accuracy might be expected to be high, reinforces what we have said above about the disadvantages of a jet as a situation in which to compare measurement techniques.

4. MEASUREMENT OF $(\sqrt{\overline{u^2}})/\overline{U}$

The determination of $\overline{\gamma 2}/\overline{\Gamma}^2$ from several independent forms of the mean square of equation (2) becomes rather more accurate if $\overline{u_2}/\overline{U}^2$ is known in advance. [1] recommended the pulsed-wire anemometer as described by Bradbury and Castro [9] and by McQuaid and Wright [10] as a suitable independent

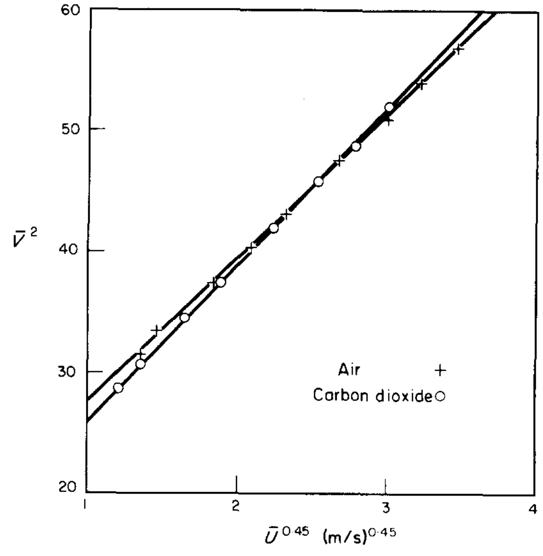

FIG. 1. Typical hot-wire calibrations in air and carbon dioxide for a 10μm dia platinum wire at an overheat ratio of 1·8.

means of measuring $\overline{u^2}/\overline{U}^2$, the latter form of the instrument being more suited to flows with low turbulence levels. However, in view of the limited nature of this study of jet flows, a simple alternative method was adopted. In any case, the method used is an application of hot-wire anemometry in flows of gas mixtures which it is of interest to describe for its own sake.

It was noted in [1] that the concentration sensitivity of a hot-wire in flows of air/carbon dioxide mixtures is low and that under certain circumstances it can be reduced to zero. This circumstance arises at the intersection of the calibrations of the wire in the two pure components. The gradients of the two calibrations are nearly equal, so that the difference in the squared voltages—on which μ directly depends—is small over an appreciable range of velocity on either side of the point of intersection, as is illustrated on Fig. 1. The velocity corresponding to the intersection depends on the overheat ratio, so that judicious choice of this can bring the region of negligibly small concentration sensitivity into the neighbourhood of the velocity of interest. The overheat ratio for which equal wire d.c. voltages are obtained in air and carbon dioxide at this velocity is first found. Then the wire is calibrated in both components at this overheat ratio.

Since the intersection is the only point at which the sensitivity is actually zero, an assessment must be made of the likely error in measurement of $(\sqrt{\overline{u^2}})/\overline{U}$ that will be incurred by assuming the sensitivity to be zero over the range of velocity covered. This error could of course be avoided by adjusting the overheat ratio to suit the new mean velocity each time the wire is moved to a new position in the flow being studied. But this procedure would require calibrations at each overheat ratio, an inconvenience which we shall see is hardly warranted by the improved accuracy which is thereby attainable.

To illustrate the condition which maximizes the error, we shall take the correlation coefficient $R_{u\gamma}$ to be positive and equal to unity so that $\overline{u\gamma} = (\sqrt{\overline{u^2}}) . \sqrt{\overline{\gamma^2}}$ an extreme unlikely to be approached in practice. It follows that the root-mean-square of equation (2) is

$$(\sqrt{\overline{v^2}}) = \delta \frac{\sqrt{\overline{u^2}}}{\overline{U}} \left[1 + \frac{\mu}{\delta} \frac{\sqrt{\overline{\gamma^2}}}{\overline{\Gamma}} \Big/ \frac{\sqrt{\overline{u^2}}}{\overline{U}} \right].$$

The sensitivity to concentration fluctuations for air/carbon dioxide mixtures at an overheat ratio of 1·3 is given in [1] as $\mu = \overline{\Gamma} . (\overline{V}_2^2 - \overline{V}_1^2)/2\overline{V}$ which follows from $\psi(\overline{\Gamma}) = \phi(\overline{\Gamma}) = \overline{\Gamma}$ for this gas pair. In view of the known relative insensitivity of $\psi(\overline{\Gamma})$ to overheat ratio we shall assume the above expression for μ to apply at other overheat ratios within the practicable range. For the conditions illustrated in Fig. 1 the second term in brackets, representing the error in taking $\sqrt{\overline{v^2}}$ to be entirely due to the velocity fluctuations, has been calculated in the neighbourhood of the intersection for a value of $[(\sqrt{\overline{\gamma^2}}/\overline{\Gamma}]/[(\sqrt{\overline{u^2}})/\overline{U}]$ of unity. The result is shown in Fig. 2. It is seen that the error estimated in this way is numerically less than 2 per cent over a range of velocity from about 5 to 15 m/s. Thus from equation 4 this variation of a factor of 3 in velocity would cater for the variation on the jet centre-line out to a distance of about 19*d* from the nozzle. The error will of course vary *pro rata* up or down if the ratio of the intensities is not unity. Measurements in an argon jet, to be described later, show that the ratio varies from about 1·4 to 2·0 over the above range of axial distance. The error can be considered comparable to or smaller than the other errors regarded as unavoidable in hot-wire anemometry—for example that due to the latitude available in fitting a straight line to a measured calibration.

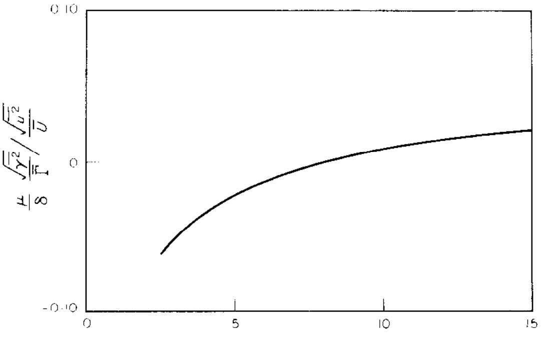

FIG. 2. Estimate of error in determination of $(\sqrt{\overline{u^2}})/\overline{U}$ for a carbon dioxide jet.

The distributions of $(\sqrt{\overline{u^2}})/\overline{U}$ on the centreline for air and carbon dioxide jets are shown on Fig. 3. Also shown are the distributions measured by Corrsin [4] and by Corrsin and Uberoi [5]. Corrsin and Uberoi found that for a lighter-than-air jet the effect of the initial density difference is to increase $(\sqrt{\overline{u^2}})/\overline{U}$ near the nozzle, but that beyond 20*d* to 25*d* from the nozzle the effect has disappeared. Our results for the carbon dioxide jet shown on Fig. 3 display a reduction in $(\sqrt{\overline{u^2}})/\overline{U}$ near the nozzle; here too the effect has almost disappeared at a distance of 20*d* from the

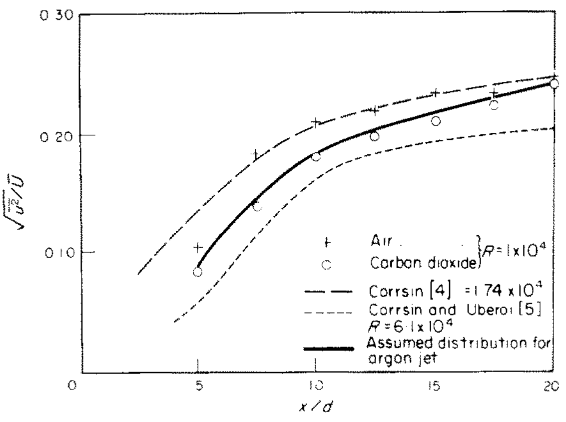

FIG. 3. Comparison of distributions of $(\sqrt{\overline{u^2}})/\bar{U}$ on jet centre-line.

nozzle. Since carbon dioxide is heavier than air, the initial behaviour, opposite to that observed by Corrsin and Uberoi for the lighter-than-air jet, is what would be expected. The air-jet measurements are in good agreement with those of Corrsin at a comparable Reynolds number.

The magnitude of the density-difference effect is seen to be small. The distribution of $(\sqrt{\overline{u^2}})/\bar{U}$ for the argon jet used subsequently has been linearly interpolated at the appropriate density-difference ratio between the distributions for air and carbon dioxide. This assumed distribution is also shown on Fig. 3.

5. MEASUREMENTS OF $\overline{u\gamma}/\bar{U}\bar{\Gamma}$ AND $(\sqrt{\overline{\gamma^2}})/\bar{\Gamma}$ IN AN ARGON JET

As shown by [1], independent forms of equation (2) are obtained for one wire operated at different overheat ratios as well as for wires of different diameter. The measurements to be discussed have been made with both 2·5 μm and 10 μm diameter wires operated at overheat ratios of 1·3 and 2·5. Since $(\sqrt{\overline{u^2}})/\bar{U}$ is known, measurements with only two combinations of wire diameter and overheat ratio are necessary to determine $\overline{u\gamma}/\bar{U}\bar{\Gamma}$ and $(\sqrt{\overline{\gamma^2}})/\bar{\Gamma}$.

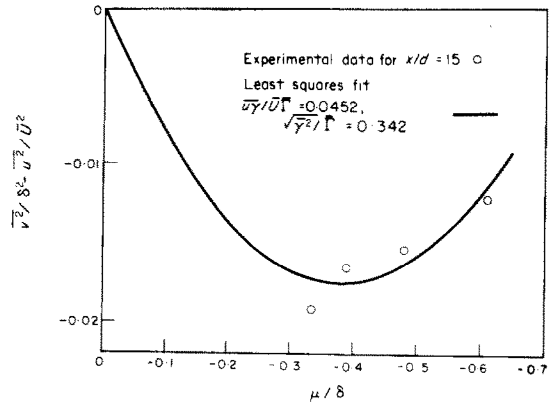

FIG. 4. An example of the method of data reduction.

However, Arya and Plate [11] have suggested the use of a least-squares procedure with redundant data to provide improved accuracy, in connection with the measurement of turbulence in flows with temperature fluctuations. The mean square of equation (2) is written as

$$\frac{\overline{v^2}}{\delta^2} - \frac{\overline{u^2}}{\bar{U}^2} = 2\frac{\overline{u\gamma}}{\bar{U}\bar{\Gamma}}\cdot\frac{\mu}{\delta} + \frac{\overline{\gamma^2}}{\bar{\Gamma}^2}\cdot\left(\frac{\mu}{\delta}\right)^2.$$

Several combinations of overheat ratio and wire diameter are used and a quadratic in μ/δ is fitted by least-squares analysis to $\overline{v^2}/\delta^2 - \overline{u^2}/\bar{U}^2$ against μ/δ, the coefficients of the fit providing $\overline{u\gamma}/\bar{U}\bar{\Gamma}$ and $\overline{\gamma^2}/\bar{\Gamma}^2$. Figure 4 shows a typical plot of the present results in the form $\overline{v^2}/\delta^2 - \overline{u^2}/\bar{U}^2$ against μ/δ, together with the fitted curve.

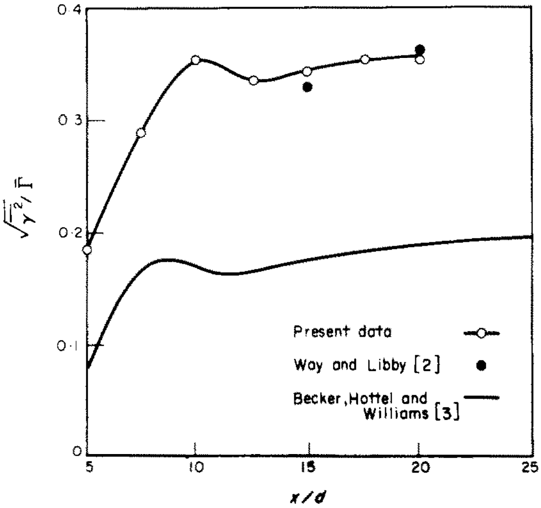

FIG. 5. Comparison of distributions of $(\sqrt{\overline{\gamma^2}})/\bar{\Gamma}$ on jet centreline.

This procedure was carried out at each axial position and the resulting distributions of $\overline{u\gamma}/\bar{U}\bar{\Gamma}$, $(\sqrt{\overline{\gamma^2}})/\bar{\Gamma}$ and $R_{u\gamma}$ are shown on Figs. 5 and 6. On Fig. 5 are also plotted the measurements of $(\sqrt{\overline{\gamma^2}})/\bar{\Gamma}$ reported by Way and Libby using a double hot-wire probe in a helium jet and the measurements of Becker *et al.* using a light-scattering technique in an air jet marked by an oil smoke. Becker *et al.* concluded that, after suitable correction for spatial resolution, their measurements in this flow situation are also appropriate to the case of constant density gas mixing. The present measurements are in good agreement with those of Way and Libby, but both sets of results disagree substantially with those of Becker *et al.* A discussion of these results will be given in the next section.

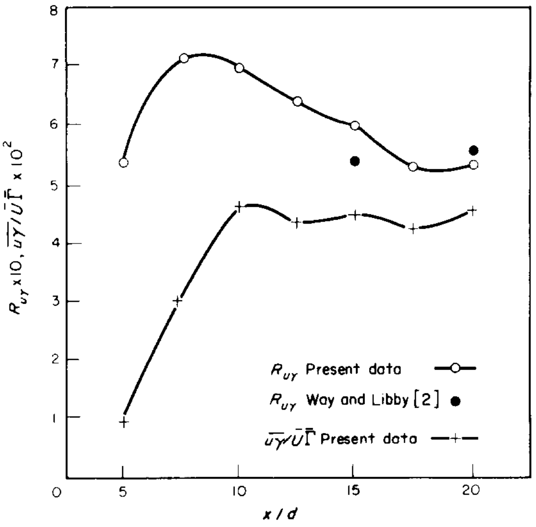

FIG. 6. Distributions of $R_{u\gamma}$ and $\overline{u\gamma}/\bar{U}\bar{\Gamma}$ on jet centreline.

On Fig. 6 our measurements of $R_{u\gamma}$ are compared with those of Way and Libby; again good agreement is shown. Way and Libby determine $\overline{u\gamma}$ from digital processing of recorded time series of U and Γ, whereas in the present case $\overline{u\gamma}$ is obtained because the measured quantity is the root-mean-square of the fluctuating wire voltage. Since two quite different ways are used to obtain $\overline{u\gamma}$ from the separate signals on each wire, the agreement found for $(\sqrt{\overline{\gamma^2}})/\bar{\Gamma}$ does not guarantee that the measurements of $\overline{u\gamma}$ will also agree. Thus the agreement obtained for the two turbulence quantities significantly improves confidence in the validity of the techniques.

The distribution of $\sqrt{\overline{\gamma^2}}$ has been plotted on Fig. 7 in a way suggested by Becker *et al.* The straight line fitted to the data is

$$\frac{\sqrt{\overline{\gamma^2}}}{\bar{\Gamma}} = \frac{0{\cdot}37}{1+0{\cdot}184\,\bar{\Gamma}/\bar{\Gamma}_0}$$

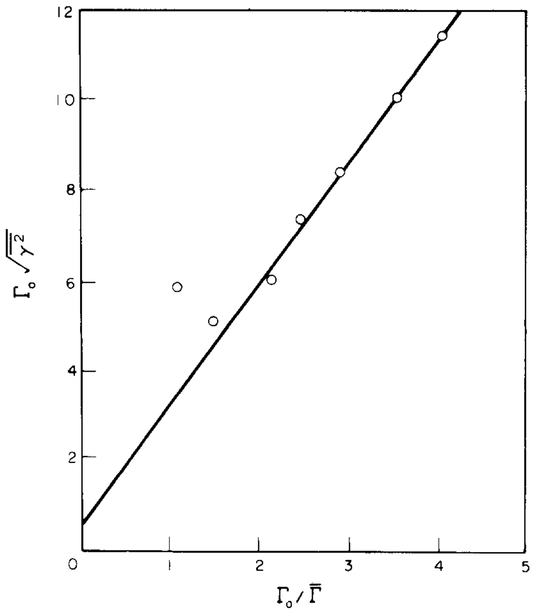

FIG. 7. Determination of $(\sqrt{\overline{\gamma^2}})/\bar{\Gamma}$ in the self-preserving region of the jet.

thus giving $(\sqrt{\overline{\gamma^2}})/\bar{\Gamma} = 0{\cdot}37$ as the asymptotic intensity in the self-preserving region of the jet.

It has already been mentioned that in the measurement of $\sqrt{\overline{u^2}}$ the hot-wire signals were not linearized; thus a possible error exists due to $u/\bar{U}$ not being small as is assumed in the analysis of the hot-wire response. (Nor indeed in the measurement of $\overline{u\gamma}$ and $\sqrt{\overline{\gamma^2}}$ has any attempt been made to consider the effect of $\gamma/\bar{\Gamma}$ not being small, which would be a problem of some complexity and would require information, not at

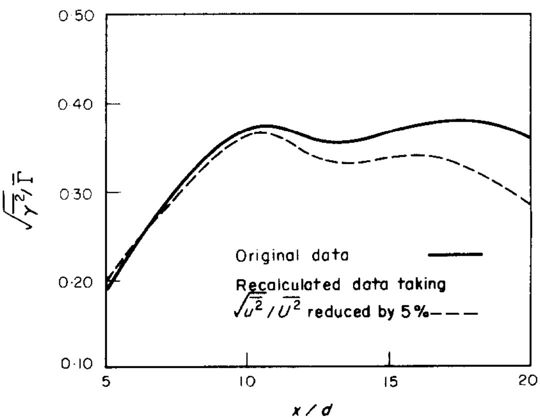

FIG. 8. Effect on $(\sqrt{\overline{\gamma^2}})/\bar{\Gamma}$ of an error in $(\sqrt{\overline{u^2}})/\bar{U}$.

present available, on the higher-order correlations in a non-homogeneous flow.) Hinze [7] indicates that, in a homogeneous flow, an unlinearized hot wire will read too high, with an error in $(\sqrt{\overline{u^2}})/\overline{U}$ of the order of 3 per cent, when used in the constant temperature mode in an isotropic turbulence with an intensity of 0·2. But the non-linearity effect is but one of the possible sources of error in the measurement of $(\sqrt{\overline{u^2}})/\overline{U}$. The question of direct interest here in view of the method of data reduction, is how sensitive the deduced values of turbulence quantities are to inaccuracy in the measurement of $(\sqrt{\overline{u^2}})/\overline{U}$. Clearly, if the values of these quantities were unduly sensitive to the values of $(\sqrt{\overline{u^2}})/\overline{U}$ used in the analysis, the usefulness of the technique would be considerably reduced. To assess this sensitivity, we have recalculated $(\sqrt{\overline{\gamma^2}})/\overline{\Gamma}$ for values of $(\sqrt{\overline{u^2}})/\overline{U}$ reduced by 5 per cent and the results are shown on Fig. 8. The effect is seen to be generally small near the nozzle but does become significant at the furthest distances downstream. It can be concluded that the technique ought not to be adopted for flows where turbulence levels are high and the uncertainties due to nonlinearity effects could be significant.

6. DISCUSSION

A considerable disagreement has been noted between the results for $\sqrt{\overline{\gamma^2}}/\overline{\Gamma}$ of Becker *et al.* and those reported here and by Way and Libby. There are a number of factors, some of which have already been touched upon, which can give rise to disagreements between investigations of jet flows. These include:

(i) *The effect of initial density difference.* In the present experiment, the relative density difference $\rho_\infty - \rho_0/\rho_\infty$ was $-0{\cdot}39$, in Way and Libby's case it was 0·858 and in that of Becker *et al.* it was zero, since the oil-smoke marker did not affect the density of the air jet. Thus the results of Fig. 5 are not correlated with the density differences in the three experiments. But detailed knowledge of the effect of density difference on turbulence is lacking. Corrsin and Uberoi found that for a heated air jet the longitudinal intentisy $(\sqrt{\overline{u^2}})/\overline{U}$ showed no effect of initial density difference beyond a distance of about 20*d* from the nozzle. This result has been corroborated by our measurements of $(\sqrt{\overline{u^2}})/\overline{U}$ discussed earlier. It would be reasonable to expect the same behaviour for $(\sqrt{\overline{\gamma^2}})/\overline{\Gamma}$, so that, whatever differences might exist near the nozzle, any effect of the different densities on the results of Fig. 5 would be tending to disappear at $x/d = 20$. In view of this, and the fact that the Way and Libby data are restricted to only two data points at $x/d = 15$ and 20, it might be expected that any difference with the present data would be small and would be masked by the effects of other factors which give rise to differences between experiments on jets. Thus no conclusion regarding the effect of initial density difference can be drawn from the comparison with the Way and Libby data, while it is also clear that initial density difference alone cannot account for the disagreement with the results of Becker *et al.*

(ii) *Miscellaneous influences.* As mentioned in the discussion on the mean flow results, these influences include the Reynolds number, the nozzle geometry, the flow conditions upstream of the nozzle (e.g. whether fully-developed pipe flow or potential flow prevailed) and the configuration of the nozzle mounting (e.g. whether the nozzle discharge was normal to a large plane surface as in Way and Libby's experiment or virtually unrestricted except by the upstream plenum chamber as in the present case). The Reynolds numbers based on nozzle diameter in the three experiments differed substantially—10^4 in the present case, $3{\cdot}29 \times 10^3$ for Way and Libby's data and $5{\cdot}4 \times 10^4$ for those of Becker *et al.* Some comparisons of the axial distributions of $(\sqrt{\overline{u^2}})/\overline{U}$ for air jets from different investigations shown by Donaldson, Snedeker and Margolis [12] display significant differences, with a trend for $(\sqrt{\overline{u^2}})/\overline{U}$ at any fixed position to decrease with increase of Reynolds number. But of course it cannot be concluded that these differences are entirely due to the Reynolds number variations. Hinze concludes that an (unspecified) Reynolds-number effect on the mean flow is present at Reynolds numbers up to 10^5 but above this value the effect is practically negligible. Thus it can be assumed that some unknown but probably small effect on the turbulence is present over the range covered by the three investigations. As for variations in nozzle geometry and the flow conditions upstream of the nozzle, these are generally held to give rise to variations in the position of the effective or virtual origin of the jet; the effects can displace the virtual origin by several nozzle diameters for the same jet Reynolds number. But for distances from the nozzle of the order of 20*d* or greater, where gradients of mean and turbulence quantities in the axial direction are small, the effect would be difficult to distinguish. However, in view of all these factors, it is probable that the close agreement with Way and Libby's results is somewhat fortuitous and is rather better than is usually expected between comparisons of jet flow results. But the disagreement with the results of Becker *et al.* is outside the expected range of variation between different experiments.

(iii) *Jet flapping.* Donaldson *et al.* observed that in the region between 10*d* and 25*d* from the nozzle, the turbulence level was particularly sensitive to changes in nozzle velocity. Their data display bumps in the axial distribution of $(\sqrt{\overline{u^2}})/\bar{U}$ which they state may have been due to flapping of the jet being studied. It is possible that this phenomenon may give rise to some of the differences observed between different investigations but again it is difficult to see that it could explain the consistent difference between the results of Becker *et al.* and those of Way and Libby and the present investigation.

Thus no satisfactory explanation of the discrepancy with the results of Becker *et al.* can be offered. It is of some interest to note, however, that the shape of the distribution of $(\sqrt{\overline{u^2}})/\bar{U}$ measured here is remarkably similar to that measured by Becker *et al.* while the method of plotting shown on Fig. 7 reproduces the behaviour noted by them.

It may be concluded from the above discussion that a jet flow is not very suitable as a means of establishing the validity of a measurement technique. Furthermore, insofar as the present technique is concerned it is a decided advantage if the velocity is low since μ/δ for air/argon mixtures increases as the velocity falls and a large relative sensitivity to concentration makes the measurement of the quantities involving γ more accurate. But a low velocity and a high Reynolds number imply a large nozzle diameter and an extended absolute traversing distance downstream. It is well known that these conditions should be avoided since low velocity jets discharging into "still" air are very sensitive to small draughts and to obstructions in the vicinity. On the other hand, a small-scale jet, less affected by these factors, demands small-scale hot wires if spatial-resolution difficulties are not to be troublesome, and this places an upper limit on the wire length and hence on the wire diameter (for minimum acceptable aspect ratio) which can be used. Thus a compromise jet velocity and Reynolds number must be accepted, with a consequent sacrifice of accuracy since both μ and the range of μ/δ are less than their maximum possible values. The technique is best suited to low-velocity, large-scale flows, and indeed was developed with the study of such flows in mind.

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MESURES DE TURBULENCE PAR L'ANEMOMETRE A FIL CHAUD DANS DES JETS NON HOMOGENES

Résumé—On a mesuré les distributions axiales de quelques quantités de turbulence dans des jets ronds s'échappant dans l'air au repos. Le premier but de l'étude est d'établir la validité d'une technique de mesure utilisant l'anémomètre à fil chaud déjà décrite par les auteurs. La distribution de l'intensité des fluctuations de vitesse longitudinale a été mesurée dans un jet de gaz carbonique et les distributions de la covariance des fluctuations de vitesse longitudinale et de concentration, de l'intensité des fluctuations de concentration ont été mesurées dans un jet d'argon. Les mesures sont comparées à celles de Way et Libby et à celles de Becker, Hottel et Williams, utilisant des techniques différentes. Un bon accord est trouvé avec les mesures de Way et Libby.

TURBULENZMESSUNGEN MIT HITZDRAHTANEMOMETERN IN HOMOGENEN STRAHLEN

Zusammenfassung—Die axiale Verteilung einiger Turbulenzgrössen in runden Strahlen, die in ruhende Luft expandieren, wurden gemessen. Die Hauptabsicht der Untersuchung war die Gültigkeit einer Messtechnik nachzuweisen, bei der Hitzdrahtanemometer verwendet wurden, wie sie kürzlich von den Autoren beschrieben wurden. Die Verteilung der Intensität von achsialen Geschwindigkeitsschwankungen wurde in einem CO_2—Strahl gemessen. Die Verteilungen der Abweichung der axialen Geschwindigkeit, die Konzentrationsschwankungen und die Intensität der Konzentrationsschwankungen wurden in einem Argonstrahl gemessen. Die Messungen werden mit denen von Way und Libby, und Becker, Hottel und Williams verglichen, die jeweils unterschiedliche Methoden verwendeten. Gute Übereinstimmung besteht mit den Messungen von Way und Libby.

ИЗМЕРЕНИЯ ТУРБУЛЕНТНОСТИ В НЕОДНОРОДНЫХ СТРУЯХ С ПОМОЩЬЮ ПРОВОЛОЧНОГО ТЕРМОАНЕМОМЕТРА

Аннотация—В работе проводилось измерение распределения в осевом направлении некоторых турбулентных величин в круглых струях, вытекающих в неподвижный воздух. Основной задачей являлось установление правильности техники измерения с помощью проволочного термоанемометра, конструкция которого была описана авторами ранее. Распределение интенсивности продольных пульсаций скорости измерялось в струе двуокиси углерода, а в струе аргона измерялись распределения корреляции продольных пульсаций скорости и концентрации, а также интенсивности пульсаций концентрации. Результаты измерений сравнивались с данными Вея и Либби, Беккера, Хоттеля и Вильямса, которые пользовались другими методами. Получено хорошее соответствие с данными Вея и Либби.