Int. J. Heat Mass Transfer. Vol. 16, pp. 819–828. Pergamon Press 1973. Printed in Great Britain

THE RESPONSE OF A HOT-WIRE ANEMOMETER IN FLOWS OF GAS MIXTURES*

J. McQUAID and W. WRIGHT

Safety in Mines Research Establishment, Department of Trade and Industry, Sheffield, England

(*Received in revised form* 28 *August* 1972)

Abstract—An investigation of the problem of measuring turbulence quantities in flows of gas mixtures by means of hot-wire anemometry is described. In view of the lack of a reliable heat-transfer law for fine wires in flows with variable gas properties, an entirely empirical approach is adopted. Attention is paid initially to the air/carbon dioxide system and it is shown that a simple calibration procedure is possible. An assessment is made to determine a suitable gas as a marker for flows in which turbulence measurements are to be made, and it is concluded that argon is to be preferred to carbon dioxide. The procedure for measuring turbulence quantities in air/argon mixtures is discussed; the optimum arrangement is a large-diameter wire operated at low overheat ratio combined with a small-diameter wire operated at high overheat ratio.

NOMENCLATURE

A,	intercept of hot wire calibration;
B,	slope of hot wire calibration;
c,	coefficient;
l,	length of hot wire;
n,	index in hot-wire response equation;
m_i, n_i,	$i = 1, 2$, etc., coefficients;
Nu,	Nusselt number;
Pr,	Prandtl number;
p, q, r,	coefficients in concentration sensitivity expression;
R,	wire resistance or Reynolds number;
u,	fluctuation in velocity about mean;
U,	instantaneous velocity;
v,	fluctuation in wire voltage about mean;
V,	instantaneous wire voltage.

Greek symbols

α,	temperature coefficient of resistance;
γ,	fluctuation in concentration about mean;
Γ,	molal concentration of second component in mixture;
δ,	sensitivity to velocity fluctuations;
ϵ,	conversion constant;
θ,	temperature;
κ,	thermal conductivity of gas;
μ,	sensitivity to concentration fluctuations;
ν,	kinematic viscosity;
ϕ,	function of concentration;
ψ,	function of concentration.

Subscripts

m,	refers to mixture of components 1 and 2;
1,	first component (air);
2,	second component;
g,	gas;
w,	wire.

An overbar indicates a time-mean quantity.

1. INTRODUCTION

FLOWS involving the turbulent mixing of two-gases are encountered in many practical situations. Quantitative knowledge of the turbulence structure of such flows is scarce mainly because of experimental difficulties which arise when the usual tool of turbulence measurement, the hot-wire anemometer, is used. The wire

---

responds to both flow velocity and concentration; and the measurements which in principle have to be made in order to obtain the intensities of the velocity and concentration fluctuations and their various cross-products become formidably tedious if a wide-ranging investigation of any particular flow situation is to be undertaken.

If conduction to the wire supports is neglected, the equation relating the electrical heat input to the wire and the convective heat loss can be written as (see for example Hinze [1])

$$\frac{V^2}{R_w} = \epsilon \pi l \kappa (\theta_w - \theta_g) \, Nu.$$

Since

$$\theta_w - \theta_g = \frac{R_w - R_g}{\alpha}$$

we then have

$$V^2 = \frac{R_w(R_w - R_g)}{\alpha} \cdot \epsilon \pi l \kappa Nu.$$

For a wire with its axis normal to the stream, the Nusselt number is usually written in the form

$$Nu = f_1(Pr) + f_2(Pr)\, R^n,$$

where f_1 and f_2 are constants for a particular gas. Hence

$$V^2 = \frac{R_w(R_w - R_g)}{\alpha} \epsilon \pi l \kappa (f_1(Pr) + f_2(Pr)\, R^n) \quad (1)$$

and for constant-temperature operation (the mode considered throughout this paper) this can be written as

$$V^2 = A + BU^n, \qquad (2)$$

where A and B are independent of velocity. The index n is usually taken as a constant, either 0·5 (King [2], Kramers [3]) or 0·45 (Collis and and Williams [4]). In a comprehensive appraisal of this heat-balance relationship, Bruun [5] has found that equation (1) is an approximation to the true functional form, the index n being in reality a function of velocity. However, he has shown that, for the mean velocities and turbulence intensities usually met in practice, the assumption of a constant value of n will give results of high accuracy provided the value of n at the mean velocity of interest is selected from his empirically established relationship. For velocities up to about 20 m/s the constant value of 0·45 given by Collis and Williams was found to be a very good approximation. In what follows we will develop our analysis in terms of n, with the value of n being selected in practical applications in the light of Bruun's results.

In applications of equation (2) to anemometry, the constants A and B must of course be known for any given wire; and for two-compnent flows knowledge of the variation of A and B with concentration is also required. Analysis of the fundamental problem of heat transfer from heated cylinders to flows with variable gas properties at the Reynolds numbers appropriate to hot-wire anemometers could provide this information and several attempts have been made toward this end.

A major difficulty is that the analyses generally deal with cylinders of infinite aspect ratio so that when the results are applied to the finite aspect-ratio wires used in practice they are liable to error because of the unaccounted heat loss to the supports. A possible further difficulty is that according to Webster [6] the wire geometry is usually difficult to measure accurately, the wires being rarely circular or of uniform diameter. The most recent analysis is due to Kassoy [7] but is restricted to Reynolds numbers rather smaller than those appropriate to commonly used wires. The analysis has been shown (Aihara, Kassoy and Libby [8]) to give good agreement with experiment but only for very large aspect-ratio wires operated at low overheat ratio and very low Reynolds numbers with guard heaters to avoid heat loss to the wire supports. These restrictions do not, of course, apply in practice so that Kassoy's analysis is of very limited practical use.

The problem of analysing the heat transfer for practical values of the Reynolds number is acknowledged by Kassoy to be mathematically intractable at present and recourse must therefore be had to experiment. This has been done by Kramers for a variety of fluids and by Collis and Williams for air only. But the same comments mentioned above regarding wire geometry must apply again since the data in both investigations referred to wires of very large aspect ratio whose use in practice would give rise to spatial resolution difficulties in a turbulent flow (Hinze [1]). Moreover the work of Collis and Williams casts doubt on the applicability of Kramers' relationship—that of direct interest to the subject of this paper. Kramers used data previously analysed by Ulsamer [9] who had fitted two separate functions to the heat-transfer data on either side of $R = 50$. Kramers stated that this change in behaviour at $R = 50$ 'does not exist in reality' and fitted a single function to all the data. But Collis and Williams unequivocally establish such a change in behaviour and attribute it to the onset of eddy-shedding. Thus their statement that "...... mean equations [covering a wide range of R] smooth out the finer details and therefore are too crude to form the basis for accurate measuring devices ......" must be held to apply to the relationship given by Kramers. In addition Kramers formulated his law in terms of a value for n of 0·5 which has been shown both by Collis and Williams and by Bruun to be inappropriate.

In view of the lack of progress on the analytical front, the solution most widely used and recommended (e.g. by Hinze [1], Bradshaw [10]) is to determine A and B for each wire by calibration against a known velocity. The sensitivity of the wire to velocity fluctuations is then readily determined.

For two-component flows with both velocity and concentration fluctuations, the pioneer work by Corrsin [11] set out the procedure necessary to measure the quantities of interest using King's form of equation (2). Subsequent workers have tended to disregard this analysis because of the unreliability of King's equation. Instead they have experimentally determined the variation of A and B with concentration and thus the sensitivity to concentration fluctuations. This method involves applying the procedure for one-component flows to a variety of mean concentrations in the range of interest (see for example Conger [12] and Montealegre *et al.* [13]); it is formidably time-consuming and tedious. The alternative of using Kramers' relation to predict the dependence of A and B on concentration cannot be recommended for the reasons already given. Recently, Wasan and Baid [14] have used the Collis and Williams law to predict the mean calibrations in mixtures of air and carbon dioxide from the calibrations in the pure components. But Collis and Williams did not explicitly investigate the effect of variable Prandtl number (on which A and B can be expected to depend). The reasonable agreement found by Wasan and Baid is fortuitously due to the near-equality of the Prandtl number for air and carbon dioxide.

There is then at the present time no alternative to an entirely experimental approach to the analysis of hot-wire response in two-component flows—or indeed in one-component flows. The principles of the experimental approach are well known. The objects of the present work are, firstly, to devise a procedure which greatly simplifies the necessary calibration; and, secondly, to determine the optimum operating conditions for the wire or wires. We have also assessed the suitability of a variety of common gases as markers for studies of turbulent mixing problems.

2. EMPIRICAL REPRESENTATION OF VELOCITY AND CONCENTRATION SENSITIVITIES

We will represent the variation with concentration of the calibration coefficients in equation (2) by polynomials of any desired degree i.e.

$$A_m = A_1 + m_1\Gamma + m_2\Gamma^2 + m_3\Gamma^3 + \dots \quad (3)$$

$$B_m = B_1 + n_1\Gamma + n_2\Gamma^2 + n_3\Gamma^3 + \dots \quad (4)$$

It can readily be shown that the equation relating time-mean quantities is

$$\bar{V}^2 = \bar{A}_m + \bar{B}_m \bar{U}^n. \qquad (5)$$

Here we have assumed, as is usual, low relative intensities of velocity and concentration fluctuations, i.e.

$$\frac{u}{\bar{U}} \ll 1 \quad \text{and} \quad \frac{\gamma}{\bar{\Gamma}} \ll 1.$$

The equation for fluctuating quantities is obtained as

$$2v\bar{V} = nB_m\bar{U}^n\frac{u}{\bar{U}} + [(m_1\bar{\Gamma} + 2m_2\bar{\Gamma}^2 + 3m_3\bar{\Gamma}^3 + \ldots) + (n_1\bar{\Gamma} + 2n_2\bar{\Gamma}^2 + 3n_3\bar{\Gamma}^3 + \ldots)\bar{U}^n] \times \frac{\gamma}{\bar{\Gamma}}.$$

This may be written as

$$v = \delta\frac{u}{\bar{U}} + \mu\frac{\gamma}{\bar{\Gamma}}, \qquad (6)$$

giving the voltage fluctuation on the wire as the sum of contributions due to the velocity and the concentration fluctuations.

It follows that

$$\delta = \frac{n(\bar{V}^2 - A_m)}{2\bar{V}}. \qquad (7)$$

We now write

$$\mu = \frac{(m_1 + n_1\bar{U}^n)\bar{\Gamma} + 2(m_2 + n_2\bar{U}^n)\bar{\Gamma}^2 + \ldots}{2\bar{V}} = \frac{p\bar{\Gamma} + q\bar{\Gamma}^2 + r\bar{\Gamma}^3 + \ldots}{2\bar{V}} \qquad (8)$$

where the new coefficients p, q, r, etc. are of course dependent on the mean velocity.

We now note that

$$\bar{V}^2 - \bar{V}_1^2 = (m_1 + n_1\bar{U}^n)\bar{\Gamma} + (m_2 + n_2\bar{U}^n)\bar{\Gamma}^2 + \ldots = p\bar{\Gamma} + \frac{q}{2}\bar{\Gamma}^2 + \frac{r}{3}\bar{\Gamma}^3 + \ldots \qquad (9)$$

Consider now the function

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

Analysis readily shows that this function is independent of velocity provided that all the calibration curves (equation (2)) for different mixtures have a common point of intersection. This result applies whether or not the index n is taken to be a function of velocity. That $\psi(\Gamma)$ is independent of velocity will presently be demonstrated by the results obtained here, while the results of Montealegre *et al.* show that the calibration lines (with a constant value of 0·5 for n) do have a common point of intersection for mixtures of air and Freon-12. Measurement of $\psi(\bar{\Gamma})$ for a variety of concentrations and velocities, and subsequent fitting of the results by a polynomial in $\bar{\Gamma}$, will thus provide the required coefficients of equation (9) in the form

$$\frac{p}{\bar{V}_2^2 - \bar{V}_1^2}, \frac{q/2}{\bar{V}_2^2 - \bar{V}_1^2}, \frac{r/3}{\bar{V}_2^2 - \bar{V}_1^2}$$

etc. This method gives a very simple procedure, since complete calibrations do not have to be carried out to determine A and B as functions of $\bar{\Gamma}$. Point values only are required at any values of concentration and velocity covering the range of interest. In the present investigation all the measurements to be discussed have been carried out at velocities less than 20 m/s, so that in fitting the calibration data the single value of 0·45 for n in equation (2) is appropriate throughout. Such measurements have been carried out on the axis of a smooth pipe in which fully developed pipe flows of air/carbon dioxide mixtures are obtained. The measurements are experimentally straightforward, the mean concentration being obtained from a wall sampling point and the axial velocity from the pressure drop over a reference length. The results are shown in Fig. 1; the velocities covered by the measurements are included. The results are for a 5-μm dia. tungsten wire 1·2-mm long operated at an overheat ratio of 1·3. (The 'overheat ratio' as used here is the ratio of the wire and gas temperatures.) Although there is some scatter,

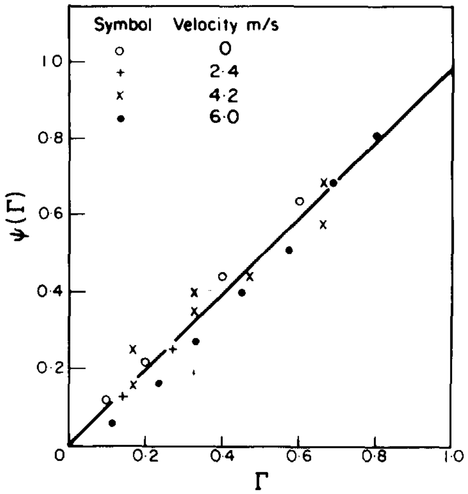

FIG 1. The function $\psi(\Gamma)$ for air/carbon dioxide mixtures. Overheat ratio = 1·3.

the data fall on a single curve (thereby showing that there is no dependence on velocity); and this curve is a straight line such that

$$\frac{\overline{V}^2 - \overline{V}_1^2}{\overline{V}_2^2 - \overline{V}_1^2} = \overline{\Gamma}.$$

Hence from equation (9) we have

$$\frac{p}{\overline{V}_2^2 - \overline{V}_1^2} = 1$$

and

$$\frac{q/2}{\overline{V}_2^2 - \overline{V}_1^2} = \frac{r/3}{\overline{V}_2^2 - \overline{V}_1^2} = \dots\dots = 0.$$

From equation (8) we get

$$\mu = \frac{\overline{V}_2^2 - \overline{V}_1^2}{2\overline{V}} . \overline{\Gamma}. \qquad (10)$$

Hence for air/carbon dioxide mixtures the calibration procedure is reduced to calibration of the wire in the pure components only, although it is necessary that the mean velocity and mean concentration be known in the flow to be investigated. Linear interpolation between the two calibrations allows the value of A_m appropriate to the mean concentration to be determined for use in evaluating the sensitivity to velocity from equation (7), while the difference between the two calibrations at the known mean velocity gives $\overline{V}_2^2 - \overline{V}_1^2$ for use in equation (10). For other gas mixtures, the function $\psi(\overline{\Gamma})$ would first need to be determined. There is no *a priori* reason to suppose that the linear relationship found for air and carbon dioxide will also hold for all other gas pairs. The relationship would also be expected to depend on the overheat ratio. But it will be independent of the diameter of the wire, because the wire diameter enters the heat-transfer law only in multiplicative combination with $\overline{U}$ (i.e. in the Reynolds number based on wire diameter). Thus again the actual calibration of each wire need be done only in the pure components.

Measurements to determine $\psi(\overline{\Gamma})$ at an overheat ratio of 1·8 showed considerable scatter because the calibrations for air and carbon dioxide are close together over a large part of the velocity range covered (0–10 m/s). For the 5-μm dia., 1·2-mm long tungsten wire, the calibrations intersect at a shallow angle at a velocity of about 8 m/s.

Thus the differences $\overline{V}^2 - \overline{V}_1^2$ and $\overline{V}_2^2 - \overline{V}_1^2$ are not much larger than the experimental error in determining the individual squared voltages. This behaviour can however be of some experimental advantage if the velocity in the flow to be studied is in the neighbourhood of the intersection. The procedure for measurement of $\overline{u^2}$ is then, of course, the same as in a one-component flow with δ determined from the wire calibration appropriate to the mean concentration.

Finally, it is of interest to note that the linear variation of $\psi(\overline{\Gamma})$ with $\overline{\Gamma}$ found for air/carbon dioxide mixtures was effectively assumed by Wasan and Baid in their application of the Collis and Williams law discussed in Section 1. They found reasonable agreement with experiment on the basis of this assumption.

3. DETERMINATION OF SUITABLE GAS

From the preceding section it follows that the sensitivity to concentration fluctuations varies directly as the difference in the squared voltages in each component at a given velocity. The fact that for air and carbon dioxide this difference is observed to be small gives rise to the scatter in the measurements on Fig. 1. Thus carbon dioxide is not a suitable choice of marking gas for studies of turbulent mixing problems if information is required on turbulence quantities in which the fluctuating concentration appears. No attempt at an investigation appears to have been carried out previously to select a suitable gas for this purpose.

An approximate assessment may be made by combining the results obtained above for air/carbon dioxide mixtures with the heat transfer law given by Kramers. Although we have earlier stated that Kramers' law cannot be expected to be sufficiently accurate to form the basis of a measuring technique, we will here only use it to place various gases on a scale of relative suitability. For this purpose no great precision is required since we are looking for comparatively gross effects. Kramers predicts that

$$\frac{A_2}{A_1} = \frac{\kappa_2 Pr_2^{0\cdot 2}}{\kappa_1 Pr_1^{0\cdot 2}}$$

and

$$\frac{B_2}{B_1} = \frac{\kappa_2 Pr_2^{0\cdot 33}/\nu_2^{0\cdot 5}}{\kappa_1 Pr_1^{0\cdot 33}/\nu_1^{0\cdot 5}}$$

where the gas properties are evaluated at the mean of the wire and gas temperatures. We use these two equations to predict the calibration of a wire in a secondary gas from the experimentally determined calibration in air. We will assume that the linear relation for μ (equation (10)) is valid for all the gases considered; this assumption should be sufficiently accurate for our present purposes. The criterion of suitability which we choose is that μ should be as large as possible compared to δ. (We shall see later that while this is a necessary condition it is not sufficient to ensure ease of measurement of concentration fluctuations.) Both μ and δ are directly calculable under the above assumptions once a calibration in air has been determined. This was taken as that for a 5-μm tungsten wire, 1·2-mm long at an overheat ratio of 1·8, a common wire configuration and operating condition. The sensitivities were determined for a mean concentration of 50 per cent and a mean velocity of 6 m/s. The results of the calculation are shown in Table 1 for a selection of commonly available gases. It is clear that hydrogen, helium and methane are very suitable on these grounds; but they may be excluded (particularly for large scale experimentation) on grounds of cost or flammability. It should also be mentioned that Kassoy [7] and Tombach [15] have found that difficulties arise with helium due to its low thermal accommodation coefficient. Argon emerges as the most suitable of the remainder: it is non-toxic and relatively cheap. All experimental results hereafter refer to air/argon mixtures.

Table 1. Sensitivity ratios at a velocity of 6 m/s and a concentration of 0·50 for a 5-μm dia. tungsten wire at an overheat ratio of 1·8

Gas	μ/δ
Carbon dioxide	−0·0735
Argon	−1·02
Hydrogen	−5·74
Oxygen	+0·087
Helium	+4·95
Methane	+1·345
Nitrous oxide	+0·133
Ammonia	+0·837
Acetylene	+0·617

4. SENSITIVITY TO CONCENTRATION FLUCTUATIONS IN AIR/ARGON MIXTURES

The function $\psi(\bar{\Gamma})$ for air/argon mixtures has been determined for three values of overheat ratio; the results are shown in Figs. 2–4. Again the range of velocity covered by these data is within the range in which a constant value of 0·45 for the index n in equation (2) is acceptable. In addition, the results in Fig. 3 are for wires of two different diameters. It is clear from the much reduced scatter that measurements in air/argon mixtures are rather more accurate

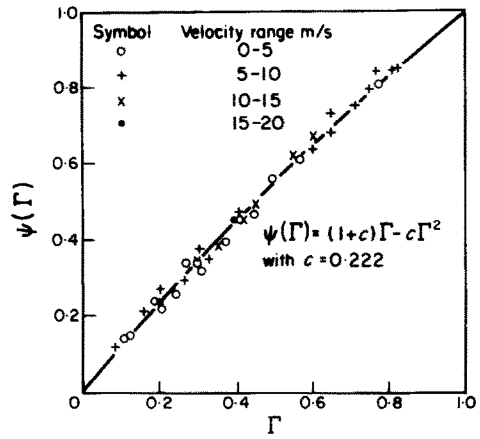

FIG. 2. The function $\psi(\Gamma)$ for air/argon mixtures. Overheat ratio = 1·3.

than in air/carbon dioxide mixtures. No effect of diameter or velocity is apparent, confirming to a much higher degree of accuracy the conclusions reached for air/carbon dioxide mixtures. We also see that the linear function of $\psi(\bar{\Gamma})$ which was fitted to the results for air/carbon dioxide mixtures does not hold for air/argon mixtures. The function

$$\psi(\bar{\Gamma}) = (1 + c)\bar{\Gamma} - c\bar{\Gamma}^2 \qquad (11)$$

is shown fitted to the data in the three figures; the value of c obtained by a least-squares fit is also shown in each case. In view of the slow variation of c with overheat ratio linear interpolation between the values quoted will suffice for intermediate overheat ratios. Combining equations (9) and (11) we obtain

$$p = (1 + c)(\bar{V}_2^2 - \bar{V}_1^2),$$

$$q = -2c(\bar{V}_2^2 - \bar{V}_1^2), r = \ldots\ldots = 0,$$

and from equation (8)

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

where

$$\phi(\bar{\Gamma}) = (1 + c)\bar{\Gamma} - 2c\bar{\Gamma}^2.$$

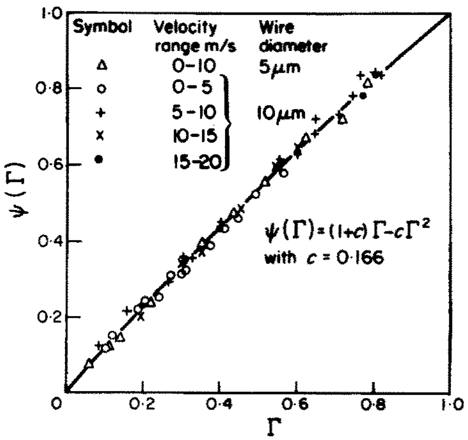

FIG. 3. The function $\psi(\Gamma)$ for air/argon mixtures. Overheat ratio = 1·8.

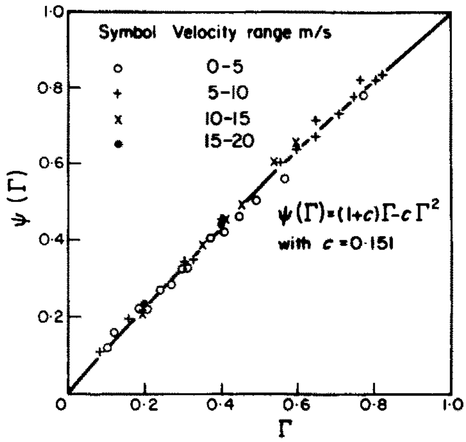

FIG. 4. The function $\psi(\Gamma)$ for air/argon mixtures. Overheat ratio = 2·5.

5. OPERATING CONDITIONS

Two independent forms of equation (6) are needed to determine the two unknowns $u/\bar{U}$ and $\gamma/\bar{\Gamma}$; these independent forms are obtained for different values of the ratio μ/δ. The accuracy with which $u/\bar{U}$ and $\gamma/\bar{\Gamma}$ can be determined depends on the amount by which the two values of μ/δ can be made to differ from each other. In this section we shall discuss how μ/δ can be experimentally varied and the order of the variation obtainable. It may be mentioned here that Way and Libby [16] have developed a double-wire probe in which one wire thermally interferes with the other so that the usual heat transfer law (equation (2)) is not obeyed by one of the wires. In this way they obtain large differences in μ/δ for the two wires. We will confine our attention to attempting to do this with wires which always obey equation (2).

There are in principle only two ways by which μ/δ can be varied: by altering the wire diameter or the wire temperature. It is clear from equation (1) that both the temperature coefficient of resistance (the only wire-material property entering the heat-balance equation) and the wire length can be combined with the voltage in the analysis leading to equation (6). Thus these properties affect μ and δ equally. Corrsin, on the basis of King's equation, found that μ/δ was independent of wire temperature. But the results to be presented below indicate that μ/δ does vary with wire temperature, so that conclusions based on King's equation should be treated with caution. This behaviour broadens the scope available for obtaining widely different values of μ/δ. There are of course limits on the range of permissible wire diameter, the lower limit being set by the requirement of adequate strength. Large-diameter wires are associated with long lengths, since the aspect ratio must be maintained above a value of about 200, and these longer lengths introduce spatial resolution difficulties. (For a discussion of these limitations, see Hinze [1] and Bradshaw [10].) The finding that a change of overheat ratio does indeed change μ/δ for a given wire is therefore of importance to the feasibility of hot-wire measurements of turbulence in gas mixtures. This finding is entirely empirical; in view of the lack of a reliable heat-transfer law no systematic prediction can be given of the effect.

Measurements for various combinations of wire diameter, material and operating temperature have been made and the results are summarised in Table 2. This gives the ratio μ/δ for a velocity of 6 m/s and a mean concentration of argon in air of 50 per cent. The optimum pair of conditions—giving maximum change in μ/δ—occurs for a large-diameter wire operated at low overheat ratio combined with a small-diameter wire operated at high overheat ratio. For this latter arrangement it is seen that, for equal intensities, the contribution to the hot-wire signal due to concentration fluctuations would be about equal to the contribution due to velocity fluctuations. Although results for tungsten wires are included in Table 2 it is preferable in practice to use platinum wires, which can be operated at a higher temperature without oxidising.

Table 2. Experimental sensitivity ratios for an air/argon mixture at $\bar{U}$ = 6 m/s and $\bar{\Gamma}$ = 0·50

Overheat ratio	2·5-μm dia. Platinum	5-μm dia. Tungsten	10-μm dia. Platinum	12·5-μm dia. Tungsten
1·3	−0·761	−0·534	−0·515	−0·486
1·8	−0·844	−0·587	−0·551	—
2·5	−1·010	—	−0·578	—

If instantaneous signal-recording facilities are available then two wires operated side by side are sufficient. If, as is more often the case, only rms voltages can be measured, then the covariance of u and γ also contributes to the measured signal, so that three independent forms of the mean square of equation (6) are needed. With two wires operated side by side, the rms sum or difference of the signals, in addition to the root-mean-squares of the separate signals on each wire, are sufficient. Otherwise, three combinations of wire diameter or overheat ratio are required.

A measurement problem of the same type is encountered in flows with temperature fluctuations; the measurement procedure in this case has been discussed by Arya and Plate [17]. They concluded that the optimum procedure is to measure one of the intensities independently—in their case that of the temperature fluctuations, measured with a resistance thermometer—and to fit by least squares a large number of independent observations to the mean square of equation (6). In the case of flows of gas mixtures, Montealegre *et al.* [13] were not successful in attempts to measure the concentration fluctuations independently using a sonic aspirator probe. A practicable method of independently measuring the intensity of velocity fluctuations is to use a pulsed-wire anemometer as described by Bradbury and Castro [18] and McQuaid and Wright [19].

We have mentioned in Section 3 that the criterion of large μ/δ is not in itself sufficient to ensure ease of measurement. A large change of μ/δ within the range of variation of the adjustable wire parameters—diameter and overheat ratio—is also required. Since δ increases with overheat ratio for all gases, it would be advantageous if μ were to decrease. This is the case for air/carbon dioxide mixtures—for which unfortunately μ/δ is small—while for air/argon mixtures, for which μ/δ takes reasonable values, μ also increases with overheat ratio and the range of μ/δ available is reduced. But a comprehensive theory (or extensive experimentation) would be needed to identify the gas with the ideal properties of large μ/δ and a large change of μ/δ within the ranges of practicable overheat ratios and wire diameters.

ACKNOWLEDGEMENTS

We wish to acknowledge the benefit of several useful discussions with Mr. A. Mercer and the assistance of Mr. D. W. Milne with some of the numerical work.

REFERENCES

1. J. O. Hinze, *Turbulence.* McGraw-Hill, New York (1959).
2. L. V. King, On the convection of heat from small cylinders in a stream of fluid, *Phil. Trans. R. Soc.* **214A**, 373–408 (1914).
3. H. Kramers, Heat transfer from spheres to flowing media, *Physica* **12**, 61–80 (1946).
4. D. C. Collis and M. J. Williams, Two-dimensional convection from heated wires at low Reynolds number, *J. Fluid Mech.* **6**, 357–384 (1959)
5. H. H. Bruun, Interpretation of a hot-wire signal using a universal calibration law, *J. Phys. E* **4**, 225–231 (1971)
6. C. A. G. Webster, An experimental study of a density stratified shear flow, Ph.D. Thesis, University of Manchester (1962).
7. D. R. Kassoy, Heat transfer from circular cylinders at low Reynolds numbers. 1. Theory for variable property flow, *Physics Fluids* **10**, 938–946 (1967).
8. Y. Aihara, D. R. Kassoy and P. A. Libby, Heat transfer from circular cylinders at low Reynolds numbers. II. Experimental results and comparison with theory, *Physics Fluids* **10**, 947–952 (1967).
9. J. Ulsamer, *Forschung* **3**, 94 (1932).
10. P. Bradshaw, *An Introduction to Turbulence and its Measurement.* Pergamon Press, Oxford (1971).
11. S. Corrsin, Extended applications of the hot-wire anemometer, NACA Tech. Note 1864 (1949).
12. W. L. Conger, The measurement of concentration fluctuations in the mixing of two gases by hot-wire anemometer techniques, Ph.D. thesis, University of Pennsylvania (1965).
13. A. Montealegre, G. J. D'Souza and H. Weinstein, Evaluation of turbulence correlations in a coaxial flow of dissimilar fluids, NACA C.R.—961 (1968).
14. D. T. Wasan and K. M. Baid, Measurement of velocity in gas mixtures: hot-wire and hot-film anemometry,
15. I. H. Tombach, Velocity measurements with a new probe in inhomogeneous turbulent jets, Ph.D. thesis, California Institute of Technology, Pasadena, California (1969).
16. J. Way and P. A. Libby, Application of hot-wire anemometry and digital techniques to measurements in a turbulent helium jet, AIAA Paper No. 71–201 (1971).
17. S. P. S. Arya and E. J. Plate, Hot-wire measurements in non-isothermal flow, *Instrums Control Syst.* **42**, 87–90 (1969).
18. L. J. S. Bradbury and I. P. Castro, A pulsed-wire technique for velocity measurements in highly turbulent flows, *J. Fluid Mech.* **49** (4), 657–692 (1971).
19. J. McQuaid and W. Wright, Measurement of turbulent fluctuating velocities in flows of gas mixtures using a pulsed-wire anemometer, to be published.

LA REPONSE D'UN ANEMOMETRE A FIL CHAUD DANS DES ECOULEMENTS DE MELANGES GAZEUX

Résumé—On étudie le problème de la mesure des grandeurs de turbulence dans des écoulements de mélanges gazeux à l'aide d'un anémomètre à fil chaud.

Etant donnée l'absence d'une loi sûre concernant le transfert thermique pour des fils fins dans des écoulements où les propriétés des gaz sont variables, on a adopté une approche entièrement empirique. L'attention est initialement portée sur le système air/dioxyde de carbone et on montre qu'une opération simple d'étalonnage est possible. Une évaluation a conduit à la détermination d'un gaz approprié en tant que marqueur pour des écoulements dans lesquels on doit faire les mesures de turbulence et on en conclut que l'argon doit être préféré au dioxyde de carbone. La méthode de mesure des quantités de turbulence dans des mélanges air/argon est discutée, l'arrangement optimal est un fil de grand diamètre utilisé à un faible rapport de surchauffe, combiné à un fil de faible diamètre utilisé à un grand rapport de surchauffe.

DIE ANSPRECHEMPFINDLICHKEIT EINES HITZDRAHTANEMOMETERS IN STRÖMUNGEN VON GASGEMISCHEN

Zusammenfassung—Eine Untersuchung des Problems der Messung des Turbulenzgrades bei Strömungen von Gasgemischen mit Hilfe der Hitzdrahtanemometrie wird beschrieben. Da verlässliche Wärmeübergangsgesetze für dünne Drähte bei veränderlichen Gaseigenschaften fehlen, wird das Problem rein empirisch behandelt. Zunächst wird das System Luft-Kohlendioxid untersucht und es wird gezeigt, dass ein einfaches Eichverfahren möglich ist. Zusätzlich wird ein geeignetes Markierungsgas für die Strömungen bestimmt, in denen Turbulenzmessungen vorgenommen werden sollen. Dafür erweist sich Argon geeigneter als Kohlendioxid.

Das Verfahren, in Luft-Argon-Gemischen den Turbulenzgrad zu bestimmen, wird besprochen. Als optimale Auslegung ergibt sich ein Draht mit grossem Durchmesser und niedrigem Überhitzungsverhältnis kombiniert mit einem Draht kleinen Durchmessers und hohem Überhitzungsverhältnis.

ПРИМЕНЕНИЕ ТЕРМОАНЕМОМЕТРА В ПОТОКАХ ГАЗОВЫХ СМЕСЕЙ

Аннотация—Описывается исследование возможности измерения турбулентности в потоках газовых смесей термоанемометром. Ввиду отсутствия надежного закона переноса тепла для тонких проволочек в потоках газов с переменными свойствами используется чисто эмпирический подход. Вначале рассматривается система воздух-двуокись углерода, и показана возможность проведения простой тарировки датчиков. Была предпринята попытка определить подходящий газ в качестве маркёра при измерении турбулентности потока, и сделан вывод, что для этих целей лучше использовать аргон, а не двуокись углерода. Обсуждается методика измерения турбулентности в смесях воздуха с аргоном. Оптимальным устройством для измерения является проволочка большого диаметра при небольшой величине перегрева в сочетании с проволочкой малого диаметра при большой величине перегрева.