APPLICATION OF A COLOUR SENSITIVE DYE TO THE MEASUREMENT OF CONCENTRATION IN A TURBULENT JET

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ABSTRACT

The cumulative probability of a specified concentration throughout a turbulent jet was measured utilizing digital image analysis of photographs taken of a coloured jet. The whole field contained a pH sensitive dye. A jet of an aqueous base solution was introduced through an orifice into an environment containing an aqueous acid solution. As mixing proceeded, the source fluid was eventually neutralized by the entrained environment fluid, at which time the indicator dye changed colour. The change marked a specific concentration of the source fluid which was controlled during the experiments. Each photograph shows the instantaneous distribution of all the fluid for which the concentration exceeds the given concentration at the time the picture was taken. Analysis of the mean colour density obtained by averaging a large number of images yields the cumulative probability distribution for one concentration as a function of both radial and axial position within the jet. Repeating the experiment for a range of concentrations permits the cumulative probability density function to be derived. From this the statistical properties of the turbulent concentration field can be obtained.

INTRODUCTION

The round turbulent jet is perhaps the most common mechanism encountered in engineering to produce mixing. The structure and shape of the instantaneous concentration fields have been studied for various applications. However, most measuring techniques are limited by the size of the probe. This size is several orders larger than the expected concentration fluctuations contained in the material surfaces the thickness of which is of the order of the Batchelor Microscale (Corriveau & Baines 1993). The current study measured the concentration field within a turbulent jet with an non-intrusive scheme by exploiting the attenuation characteristics of a pH sensitive dye. This overcomes the resolution problems associated with conventional probes.

EXPERIMENTAL TECHNIQUE

The use of pH sensitive dyes combined with an acid-base chemical reaction was first mentioned in Hottel's survey paper (1953). Since then, several investigators have used similar chemical reactions to study turbulent mixing. This paper demonstrate a unique method of analysing the data from experiments using a pH sensitive dye to produce the concentration probability distribution of a turbulent jet.

The addition of an acid to a basic solution containing a colour sensitive dye produces a change in colour at a particular value of pH. This principle has been applied to a turbulent jet of water in a tank. Both the environment and the source contain the same concentration of pH indicator. The environment is a weak aqueous solution of hydrochloric acid. The source flow is made basic by the addition of sodium hydroxide, the concentration of which is a multiple κ of that of the acidic environment. The dye used in this study was phenol red which is deep red when basic and changes colour to pale yellow at a pH of 7.6. The reaction time for the colour change is extremely short and is a diffusion limited chemical reaction. When the source and environment fluids are mixed continuously, the colour changes from red to yellow when the ratio of the local concentration to that in the source is given by

$$c = 1 / (1 + \kappa) \qquad (1)$$

This colour change will occur in any flow when an acid and base are mixed in the presence of the dye. A photograph shows zones of red and yellow, the interface of which is a surface of constant c.

RESULTS

The data presented in this note was obtained by implementing the technique described above for a jet with a source Reynolds number of 4000. The ratio of the source and environment concentration was varied from 0.5 to 20.

Photographs

The resulting red zone looks like the brush of a turbulent flame which, indeed, is analogous. The flame front is

a surface of constant concentration, that is, the surface where the air-fuel ratio is that for combustion. Within the coloured zone one can see large dense regions which are the large eddies. These move rapidly along the flow and smaller structures become more evident with distance. At the end of the brush only the smallest zones are seen. Figure 1 is a photograph showing this development. The small patches of red move a long distance downstream before being extinguished. These are isolated zones of small turbulent strain so the weak diffusion permits the high concentration fluid to exist for a long time in the turbulent field. Measurement of the farthest penetration of these patches gives data on the maximum concentration found in the jet cross-section. Other quantitative measurements can be derived from these individual photographs but are limited because one is observing properties integrated across the full thickness of the jet. That is, although the axial location is known, the location of features in the coordinate perpendicular to the camera remains unknown.

Digital Image Processing

Some statistical properties of the concentration distribution have been obtained by averaging a large number of images and applying an inverse transform to the data. The jet was illuminated by back lighting the tank with an almost parallel light beam from a projector. Uniformity of the illumination was ensured by installing diffusing screens. The light passed through the tank and the image photographed with a charge-coupled device (CCD) camera and individual frames transferred to a frame grabber in a personal computer. Each digitized frame was 640x480 pixels in size with a resolution of 8 bits per pixel.

The images recorded the intensity in grey levels of the light received from each pixel of the image. The red fluid absorbed more energy than the yellow, so the intensity of radiation incident on the CCD image plane varied with the length of the red zones through which the light has passed. Defining α_R and α_Y as the absorptivity of the red and yellow zones, the intensity of radiation from the light beam passing through the jet is specified by Beer's Law:

$$i = i_o e^{-\alpha_R \upsilon} e^{-\alpha_Y (L - \upsilon)} \qquad (2)$$

where i_o is the initial intensity of the beam, υ is the total length of the red zones, and L is the width of the tank. Dividing this by i_b which is the background intensity measured in the absence of the jet, results in the following expression for υ :

$$\upsilon = \frac{1}{\alpha_R - \alpha_Y} \ln\left(\frac{i}{i_b}\right) \qquad (3)$$

The frames were processed to yield the total density of red at each point. At the source outlet, the length of the red zone on the centreline is D, the diameter of the jet. Applying Eq. (3) to this section determines $(\alpha_R - \alpha_Y)$ in terms of the measured intensity ratio. Thus it was not necessary to record an absolute value of the intensity, rather the relative intensity values of the background and that at the source outlet were used to calibrate the images. Once calibrated the total depth of red fluid perpendicular to the camera was found using Eq (3). The numerical value yielded the total distance in the chord of the jet cross-section at which the concentration exceeded the specified concentration and was stored in a double precision array. The brush was about 400 pixels long and 80 pixels wide at the maxi-

mum width. The frames were stored in RAM and an average taken of 80 frames. The array could then be scaled back to integer form for a visual interpretation of the average depth of red liquid through the jet perpendicular to the image plane. Figure 2 shows the mean colour density while Fig. 3 has been transformed to indicate depth. Both photographs have been contoured to accentuate the change in the mean density and depth. Along the centreline this increases downstream from the source because with mixing of high concentration source fluid the volume of red fluid increases. A maximum is reached where most of the mixed fluid is at the concentration where the colour changes. Beyond this point the density decreases as the red changes to yellow with further dilution.

Inverse Radial Transform

When a sufficient number of images are averaged then the concentration distribution was assumed axisymmetric. The floating point array, $\upsilon\,(x,y)$, has units of length and is the integral of the probability that the colour is red somewhere along the projection. The coordinate x is along the axis measured from the source, y and z are normal to and in the plane of the image and the radius r is in the y,z plane. One must solve the inverse problem to determine the radial distribution of probability from the integral across a chord of the distribution. That is,

$$\upsilon = \int_{-\infty}^{\infty} P(c)\, dy \qquad (4)$$

where $P(c)$ is probability that the concentration exceeds c at the point (x,r) and is equal to

$$P(c) = 1 - \mathrm{CDF}(c) \qquad (5)$$

and CDF is the cumulative distributions function of the concentration at the location of interest.

The solution was obtained by setting the profile of the distribution and determining the parameters by fitting the integral in Eq.(4). At the exit of the source the concentration profile is a top-hat so υ was the chord of a circle. Downstream, beyond the section of maximum red density the profile was Gaussian. In general it was assumed that the profile for each axial position was Gaussian at the edge of the jet with 1/e width of b and had a constant $P_m(c)$ over the central region of radius r_c. A routine was developed which ensured that the three parameters provided an optimum fit to υ . Figure 4 presents a typical result for the measured and fitted values and Fig. 5 shows the resulting radial distribution. Figure 6 is a plot of the centre-line probability determined from the image in Fig. 3. The width parameters are plotted in Fig. 7.

These data show that the median concentration is found at $x/D = 7.8$ for $c = 0.411$. If the probability distribution were symmetric then the median would equal the mean concentration. This value is within the range reported in the literature as quoted by Papanicolau and List(1988).

CONCLUSIONS

Repeating the experiment for several values of κ yields the cumulative probability distribution at each (x,r). This can be differentiated to define the probability distribution $p(c)$, the moments of which define the mean, intensity, skewness and kurtosis of concentration. Experiments are currently being conducted to determine the CDF at different Reynolds numbers. The digital image analysis method

presented here is a valuable tool in measuring the concentration distribution in axisymmetric flows.

REFERENCES

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Hottel H.C. 1953. "Burning in Laminar and Turbulent Fuel Jets". *Proc 4th Symp (Int) on Combustion*, pp. 97-113.

Papanicolau, P.N. and List. E.J..1988. Investigation of Round Vertical Turbulent Buoyant Jets. *J. Fluid Mech.,* Vol. 195. pp 341-391.

Figure 2.Photograph of contours of constant density of red seen through a turbulent jet for concentration 0.411, Re = 4000, source diameter = 1.24 mm.

Figure 1. Photograph of a single realization of the distribution of coloured dye within a turbulent jet. Note the almost uniform distribution of large eddies along the axis of the jet. The smaller isolated zones are remnants of eddies where the turbulent strain is very small.
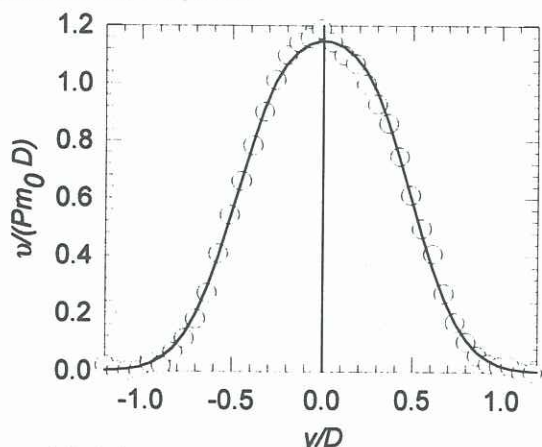
Figure 3.Photograph of contours of constant depth of red fluid through a turbulent jet for concentration 0.411, Re = 4000, source diameter = 1.24 mm.

Figure 4. Relative density of red for the cross-section of Fig. 2 at x/D = 1.82. Points are measured and line is fitted combination of top-hat and Gaussian profiles.
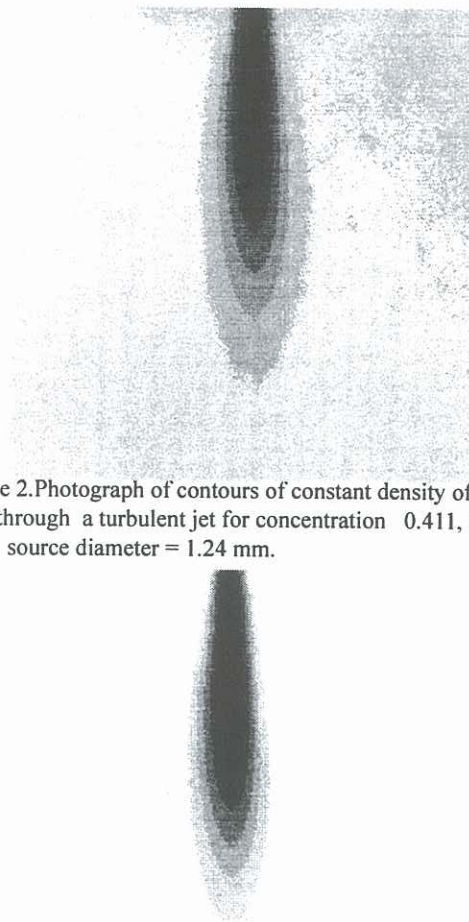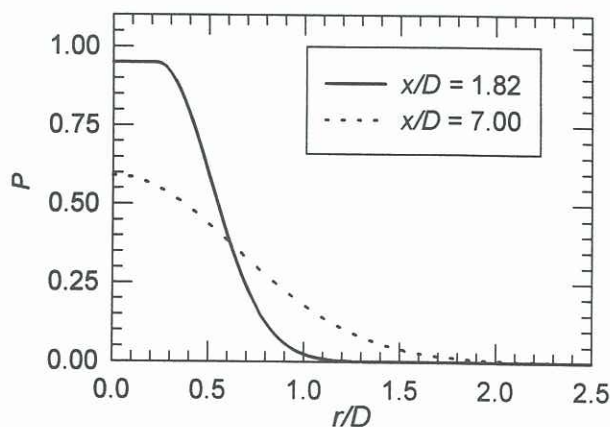
Figure 5. Radial probability for two axial positions of finding fluid meeting or exceeding a concentration of 0.411.
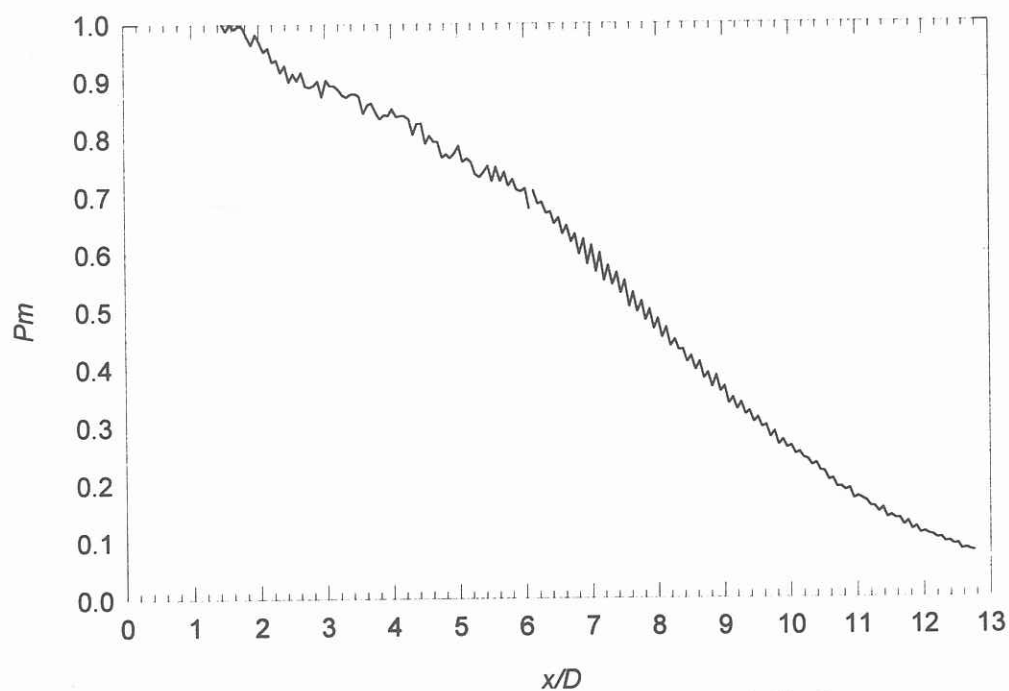
Figure 6. Probability of concentration exceeding 0.411 along centreline of jet shown in Fig. 2.
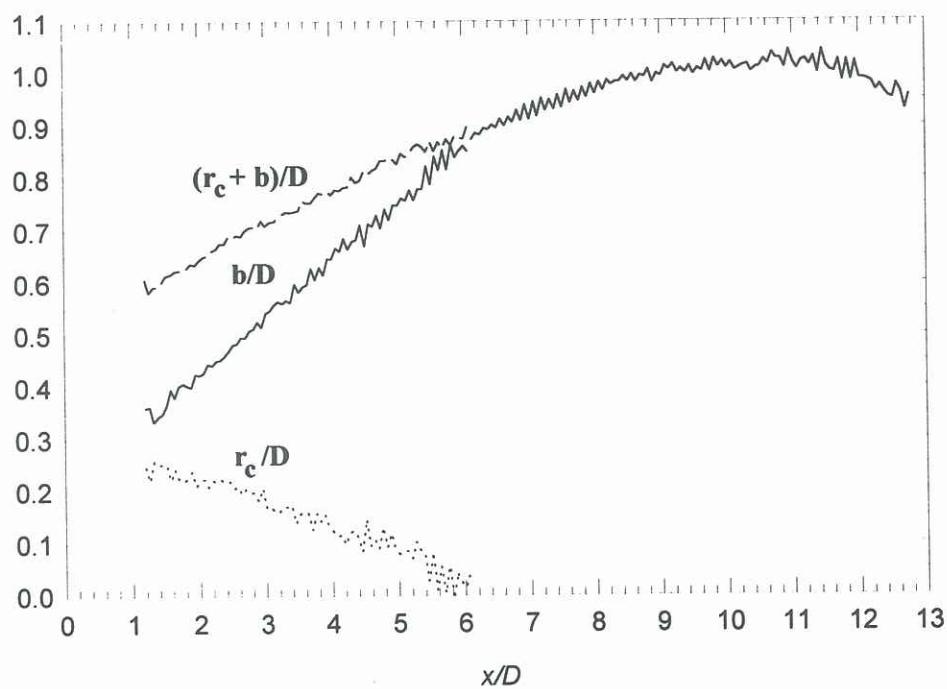

Figure 7. Widths of profiles deduced from photograph in Fig 2. r_c is radius of top-hat section and b is 1/e radius of Gaussian section.