01 Jan 1973

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ABSTRACT

Flow visualisation studies in a square duct of internal dimensions 44.5 x 44.5 mm are reported. The flow marker is a stream of opaque white dye, released from a downstream facing stationary tube, and it is photographed through the plexiglass wall of the duct. The point of dye release can be traversed in a direction perpendicular to the duct wall and three locations are investigated, two in the core of the flow and one in the near-wall region. By using 1s exposure times photographs are obtained of a dye dispersion cone and the cone angle is measured and related to the turbulence properties of the flow. Using water as the solvent various concentrations of the highly effective drag reducing polymer Polyox WSR-301 are explored and relationships obtained between cone angle and injection location, Reynolds number and drag reduction. The importance of turbulence suppression in the near-wall region of the flow is demonstrated to be closely linked with the drag reduction mechanism.

INTRODUCTION

Flow visualisation has always played a useful role in fluid mechanics, in particular assisting in the understanding and interpretation of quantitative data collected by other methods. The objects in the present study were to make visible the flow processes that occur when water flows contain dissolved high molecular weight polymers and to correlate observed changes in the flow patterns with the drag reduction achieved. Over the last ten years numerous experimental studies have established the extent to which friction in turbulent liquid flows can be reduced by the addition of small quantities of suitable polymers. The search for a satisfactory predictive theory has proved difficult, one reason for this being the difficulty in making the necessary measurements of the polymer molecular characteristics and another reason being the way in which these characteristics appear to change either in storage or in use.

Because of these ageing and degradation problems the repeatability of drag reduction data has remained consistently poor. If correlation is sought between different behavioural characteristics of polymer solutions it is necessary to use the same prepared solution and to make the measurements in as short a time as possible.

In spite of these difficulties certain general trends in polymer solution drag reduction are now well established. These include the following:

(1) The undosed flow must be turbulent.

(2) Drag reduction will only occur if the polymer is present in the near-wall region of the flow.

(3) The degree of drag-reduction achieved depends upon the molecular structure of

the polymer used; it also depends upon its molecular weight, the larger molecules (above 10^6) being the most efficient drag reducers (6).

(4) That an optimum concentration exists for each polymer and pipe size. As the pipe size increases so does the optimum concentration (5).

The evidence for the near wall requirement above is based largely on boundary layer polymer injection studies (see, for example, Reference 2). This is borne out by the author's experiments using different injection sites in the cross-section; injection on the centreline of the pipe producing a much longer delay, in terms of distance downstream, before drag reduction can be detected than injection over the whole cross-section, a result produced by Wells and Spangler (11) following a far more comprehensive programme of experiments.

The behaviour of dilute polymer solutions in flow situations where the dominating force is not wall shear stress is typified by experiments of Fabula (3) in which he towed a grid through stationary dilute polymer solution using a conventional towing tank. Investigating the one-dimensional turbulence spectrum behind the grid, Fabula was unable to detect any effects of the polymer on the measured energy spectra. However, Barnard and Sellin (1), studying the turbulence downstream from a grid of similar dimensions fixed across a water tunnel, found evidence of damping of the high frequency components in the turbulent flow structure following the upstream dosing of the flow with polyethylene oxide (WSR-301)* to give as little as 5 w.p.p.m. (parts per million by weight) concentration. In these experiments the effect of the flow contraction immediately before the grid may have been to condition the polymer solution by forming filaments, a property whose importance was stressed by Lumley (8). It was in these water tunnel grid turbulence studies that the flow visualisation technique used in the present investigation was developed.

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*Union Carbide Corporation

Townsend (10) had previously correlated dispersion cone angle measurements from photographs obtained under Newtonian open channel flow conditions with the early ultramicroscope measurements of Fage and Townend (4). Both these techniques give a deviation angle which is proportional to the relative intensity of lateral turbulent velocity v either in the form

$$\frac{v_{max}}{U_o} \qquad \text{or} \qquad \frac{\sqrt{(\overline{v^2})}}{U_o} .$$

This correlation established that values of $\overline{\theta}$, the cone angle measured from 1s exposure photographs of a diffusing dye stream, closely follow the ultramicroscope angle α in a traverse across a fully developed turbulent channel flow.

The present study establishes a relationship between the dispersion cone angle $\overline{\theta}$, measured in drag reducing fluids, and the degree of drag reduction achieved. Further, by traversing the duct with the dye injection nozzle it is possible to see how the variation in dispersion across the flow is changed when fluid drag is reduced by polymer additives.

EXPERIMENTAL FACILITY

The apparatus consisted of a square section tube, internal dimensions 44.5mm and overall length 4990mm. Flow was by gravity from an open head tank by way of a bellmouth inlet and at the downstream end the discharge fell into a volumetric measuring tank. The test pipe comprised a 3650mm initial aluminium alloy length followed by a 915mm Plexiglass observation length and finally a 425mm aluminium discharge section. The last 40 D ('diameter') length of the inlet section was used for head loss determination leaving the first 42 D for flow establishment.

The polymer solution was prepared as a concentrate (500-2000 w.p.p.m.) in 20 ℓ batches by dispersing it in ethylene glycol which was then added to the correct volume of water. The mixture was stirred gently at intervals and allowed 24 hours to achieve homogeneity before use. The concentrate was introduced to the main water flow through an X-shaped injection manifold mounted inside the bellmouth inlet. The arms of the X were aligned with the diagonals of the test pipe and each arm had two injection holes, one at the end and the other at mid-span, making eight in all. This manifold was fed by a peristaltic pump at a fixed rate of 30 ml/s. Variation in feed strength was therefore obtained by selecting the weight of polymer in the prepared batch of concentrate. The polymer used throughout was freshly purchased Polyox WSR-301 and the ethylene glycol also acted as an anti-oxydation agent.

Trials with a number of white liquids showed that diluted emulsion paint gave the best results having the right diffusion characteristics in water combined with good opacity. All photographs were made with side lighting and a black background. The dye stream was injected from a 1.5mm bore tube pointing downstream with the orifice sufficiently far away from the transverse leg to keep the dye cone out of the strongest part of its turbulent wake. In order to establish the extent to which the presence of the dye probe affected the flow downstream from it, a visual comparison was made of dye-cone dispersion from two points, one close to the top of the duct and the other the same distance above the bottom of the duct. As the dye probe entered the duct from above its effect on the downstream flow should be a minimum in the first case and a maximum in the second, however no difference was apparent between the two dye plumes except a slight positive density effect which became noticeable 10 duct diameters (400 probe diameters) downstream from the injection section. This dye injector was fixed to a carriage whose transverse location was controlled by a micrometer head. The dye reservoir was raised or lowered until the dye efflux velocity matched the local mean water velocity at each position; with the efflux velocity too great premature turbulent dispersion of the dye jet occurred, while when the efflux velocity was too low the dye jet diameter was reduced by wasting immediately after it left the orifice. The procedure finally adopted was to lower the reservoir until unmistakable wasting was evident and then to raise it until a constant diameter jet emerged.

DISPERSION CONE ANGLES

The injection of dye from a fixed point has the effect of marking fluid particles that have passed in close proximity to the orifice of the injection tube. The subsequent history of these marked particles can be recorded by either short or long exposure photographs.

Figure 1 shows a short (1 ms) exposure photograph of the dye trace injected into undosed water. It corresponds closely to previous photographs of smoke released in wind tunnels and of other neutrally-buoyant markers. Figure 2, however, is a 1 ms exposure photograph of dye released into a 20 w.p.p.m. 'Polyox' solution and the contrast with Figure 1 is striking. Both show the dye being released on the centreline of the flow (y/D = 0.50) for which $R_s = 4 \times 10^4$. Values of Fanning friction coefficient f and concentration of polymer c at this R_s value are given below in Table 1. Solvent based R_s value = 41,700 for all values of c.

Table 1

Polymer concentration c w.p.p.m.	Fanning f(x 10^{-4})
0	57
0.6	50
1.2	42
2.5	39
5	35
10	27
15	29
40	27

These photographs give a qualitative impression of the structure of the turbulence in each case but are unsuitable for quantitative measurements because, due to the short exposure time, the motion of the dye stream is "frozen" and there is no indication of the instantaneous direction of motion of the marked fluid particles. Accordingly, further

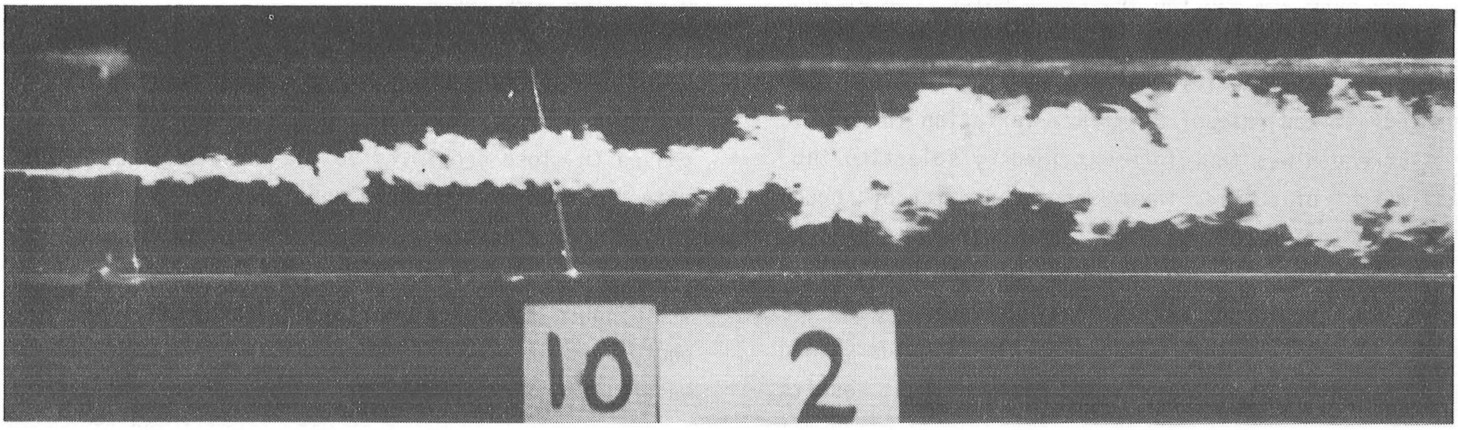

Figure 1. 1 ms exposure photograph of dye dispersion in a square duct. Water flow at $R_s = 4 \times 10^4$ ($y/D = 0.50$).

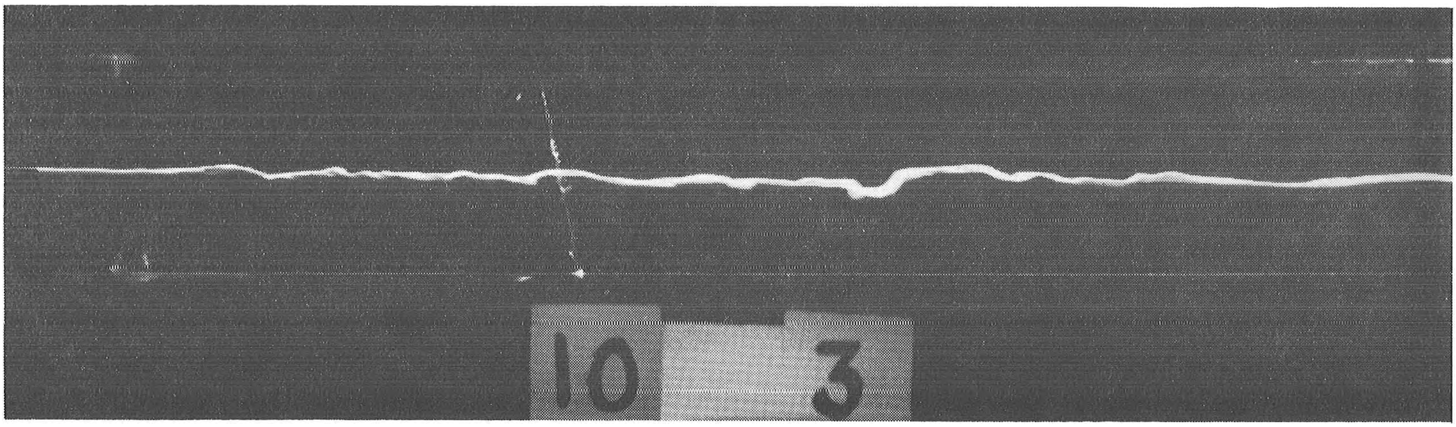

Figure 2. As Figure 1, but flow dosed with 20 w.p.p.m. of Polyox WSR-301.

photographs were taken with a 1s exposure and these effectively record the maximum lateral excursions of the marked particles.

The projection onto an axial plane of the instantaneous motion of a fluid particle is given by vector addition of its instantaneous lateral (y-direction) and forward velocity components, v and $(U_o + u)$. The resulting vector makes an angle

$$\tan^{-1} \frac{v}{(U_o + u)}$$

which can be simplified without serious error to $\tan^{-1} \frac{v}{U_o}$.* Within a small distance of the injection point, the envelope of the dye trace is generated by marked particles which possessed the maximum lateral velocity components (v_{max}) when passing the injection point; particles possessing lesser values of v will pass into the interior of the cone. Thus close to the injection point the cone angle θ of the envelope is related to v_{max} by the relationship:

$$\tan \frac{\theta}{2} = \frac{v_{max}}{U_o}$$

and so values of $\frac{v_{max}}{U_o}$ can be obtained from photographs of the dye trace provided that the exposure is long enough for the recorded value of v_{max} to be significant. Values of $\bar{\theta}$ used in the following section are the average values of the cone angles measured from five consecutive 1s photographs.

RESULTS

Three flow rates were investigated corresponding to R_s values of 2, 3, and 4 x 10^4

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*$\tan \theta/2 = \frac{v}{U_o + u} = \frac{v}{U_o} [1 - \frac{u}{U_o} + (\frac{u}{U_o})^2 \cdots]$,

so that if $\frac{u}{U_o} << 1$, percentage error in assuming $\tan \frac{\theta}{2} = \frac{u}{U_o}$ is $\frac{u}{U_o}$ x 100. Turbulent pipe flow will have an r.m.s. value for this term of about 7% in the core rising to about 20% close to the wall. This will not invalidate the trends reported in Figures 3, 4 and 5.

respectively. By selecting three polymer concentrate strengths values of c, the final polymer concentration in the square duct, were obtained over the range 5 - 40 w.p.p.m.

Figures 3, 4 and 5 show values of $\tan \frac{\bar{\theta}}{2}$ corresponding to the three dye injection positions chosen (y/D values). Figure 3 shows results for dye injection on the centreline of the duct and also plotted on this graph are the results of Barnard and Sellin for grid turbulence. The close agreement between the present results and those obtained with the grid suggests a similarity of mechanism between the non-Newtonian effects apparent in these grid turbulence experiments and the drag reduction achieved in pipe and duct flow. Figure 4, giving the results of quarter-span dye injection, shows no significant divergence from Figure 3 but on the other hand the near-wall dye injection results given in Figure 5 indicate an unmistakable effect of polymer dosing as the duct wall is approached.

Values of $\tan \frac{\bar{\theta}}{2}$ for water rise as the wall is approached while the reverse trend is apparent in the dilute polymer solution. This confirms earlier statements that it is in this near-wall region that drag reduction is initiated by the suppression of the momentum transfer mechanism perpendicular to the solid boundary (2). Figures 6 and 7 show 1s exposures of near-wall dye injection respectively without and with polymer dosing. In no other region of the flow is the effect of the polymer more strongly marked than in this near-wall region. Values of θ are more difficult to measure close to the wall (y/D = 0.05) since the spreading of the dye stream is impeded on one side. The method finally adopted was to measure θ/2 directly using the semi-cone farthest from the wall.

Figure 8 shows the variation of $\tan \frac{\bar{\theta}}{2}$ values with $\frac{y}{D}$ and reveals clearly this pronounced effect of the polymer dosing in the near-wall region. Townsend's results obtained from measuring dispersion cone angles for water flowing in a 250mm wide open channel are also shown as a further example of a normal turbulent flow (R_s = 1.8 x 10^4). These points are shown to be in good agreement with the

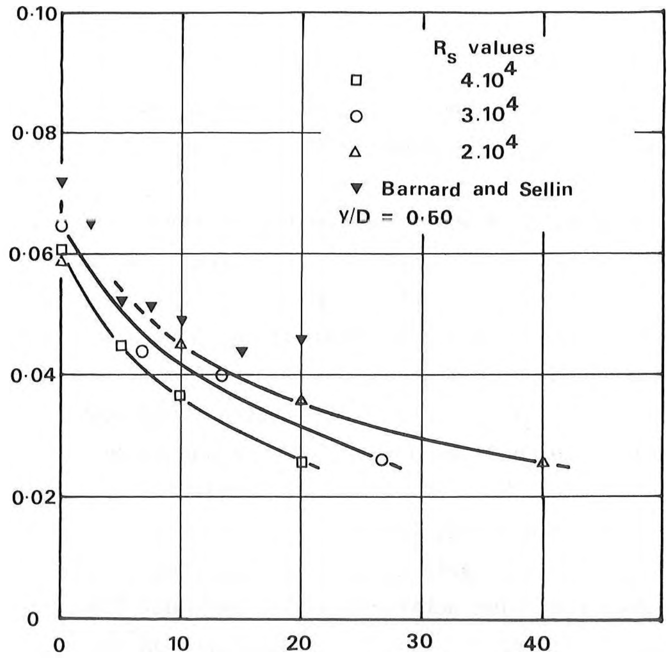
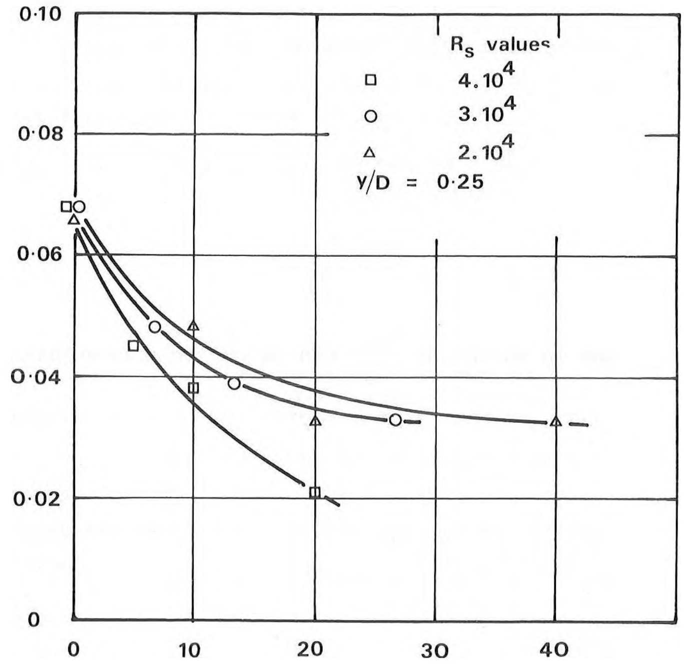


Figure 3. Values of $\tan \frac{\overline{\theta}}{2}$ against polymer concentration c for dye injection on duct centreline (y/D = 0.50). Results of Barnard and Sellin for grid turbulence shown for comparison.

Figure 4. Values of $\tan \frac{\overline{\theta}}{2}$ against c for quarter span dye injection (y/D = 0.25).



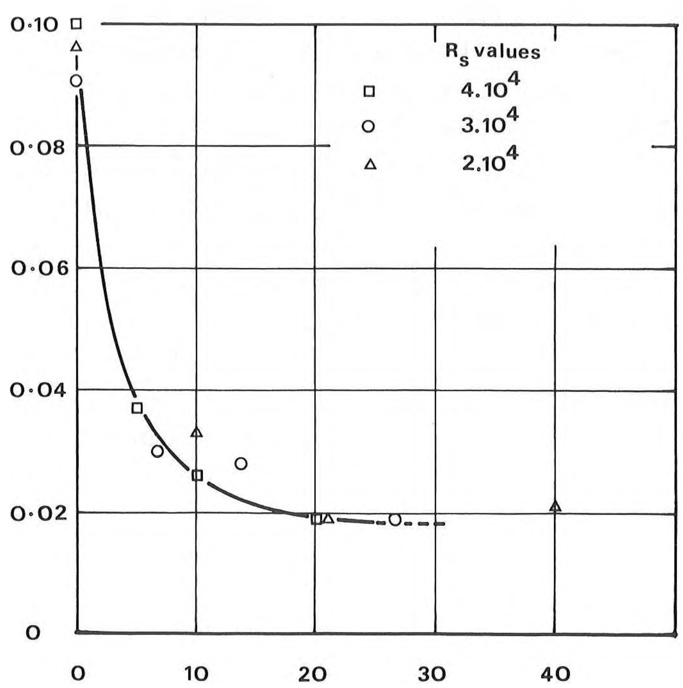


Figure 5. Values of $\tan \frac{\overline{\theta}}{2}$ against c for near-wall dye injection (y/D = 0.05).

Figure 6. Near-wall injection of dye into a square duct (y/D = 0.05). Water flow at R_s = 4 x 10^4, exposure time 1 s.

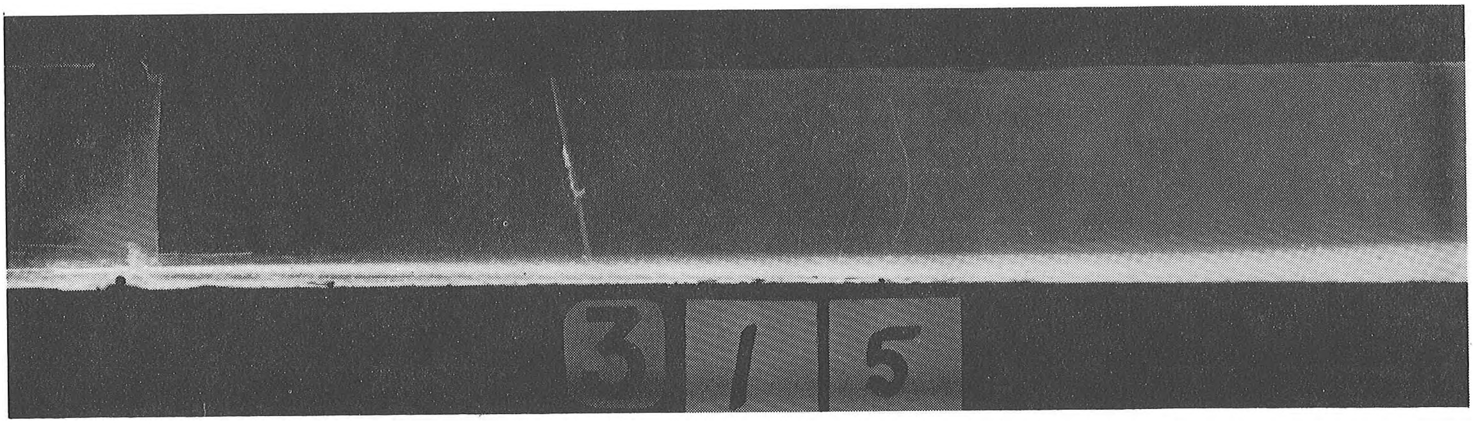


Figure 7. As Figure 6, but flow dosed with 20 w.p.p.m. of Polyox WSR-301.

water-only flows in the square duct over the range of R_s values covered.

Finally, a comparison is made between dye dispersion and drag reduction. Figure 9 shows curves based on the values of tan $\frac{\theta}{2}$ obtained at $R_s = 4 \times 10^4$ plotted on the same polymer concentration axis as the drag reduction values achieved under the same condition. Drag reduction is related to the hydraulic gradient under constant R_s conditions and the head loss ΔH plotted in Figure 9 is directly proportional to the hydraulic gradient.

DISCUSSION

The result of this investigation appear to confirm the conclusions of Donahue,et al. (2) as regards the significance of the role played by the near-wall region in fluid drag reduction by polymer additives. Whereas Donahue's data was obtained by identifying low energy bursts from the wall layer and analysing their spatial distribution, the present approach is to record the time integrated paths of marked fluid particles and to infer, from measurements of the resulting dispersion cone angles, changes in the spanwise momentum transfer mechanism. Figure 9 shows the extent to which these correlate with the drag reduction achieved in this particular duct. It will be seen that the ΔH points reach a steady value at a c-value between 10 and 20, which is in agreement with previous findings in small pipes, and the near-wall curve (y/D = 0.05) for cone angle shows a similar trend. The curves corresponding to cone angles in the core of the flow appear to reach their steady values at concentrations outside the range covered at $R_s = 4 \times 10^4$. This again points to the significance of near-wall flow in the control of fluid drag reduction by additives.

Logan (7) reports measurements of axial and radial turbulence intensities in a square pipe 12 mm x 12 mm using a 50 w.p.p.m. solution of an unspecified grade of Polyox. His measurements are made with a laser Doppler system at an L/D value of about 50 and an R_s value of 26,000. In the present investigation these quantities are 87 and 41,700 at the highest velocities used. Logan reports a 25% reduction in radial turbulence levels at the centreline and a 50% reduction at y/D = 0.05, both values considerably smaller than those indicated in Figure 8. These differences may be due to any of the following reasons: (a) different grades of polymer, (b) different c values, (c) the different measurement systems used. Figure 8 supports the view that variations in R_s values are of secondary importance.

The dye trace shown in Figure 2 suggests transition behaviour and it is possible that the dissolved polymer delays the establishment of the fully developed velocity profile beyond the dye injection point (82 'diameters' from the inlet). Seyer and Metzner (9) draw attention to the very long pipe lengths required for flow establishment in drag reducing solutions and this suggests that both the present study and Logan's work may be concerned with incompletely established turbulent flow at R_s values in the range 20,000 - 40,000.

Seyer and Metzner also present values of turbulence intensities for flows of various drag reducing fluids in a 25 mm pipe. In general their results for radial turbulence levels display the same tendencies as those reported here and they also recognise that their drag reducing flows may be transitional in character (no L/D values given).

These experiments do not give any precise information about energy spectra but some qualitative results can be inferred from the 1 ms exposure photographs. Comparison of Figures 1 and 2 shows that the effect of the additive is to inhibit (apparently completely) the high frequency components that are present in normal turbulent flow which are responsible for the dye dispersion visible in Figure 1. Photographs taken close to the boundary at 1 ms exposure (not shown) reveal an even less disturbed stream of dye since the close proximity of the wall tends to damp out the low frequency disturbances still apparent in the dosed flow at the centreline.

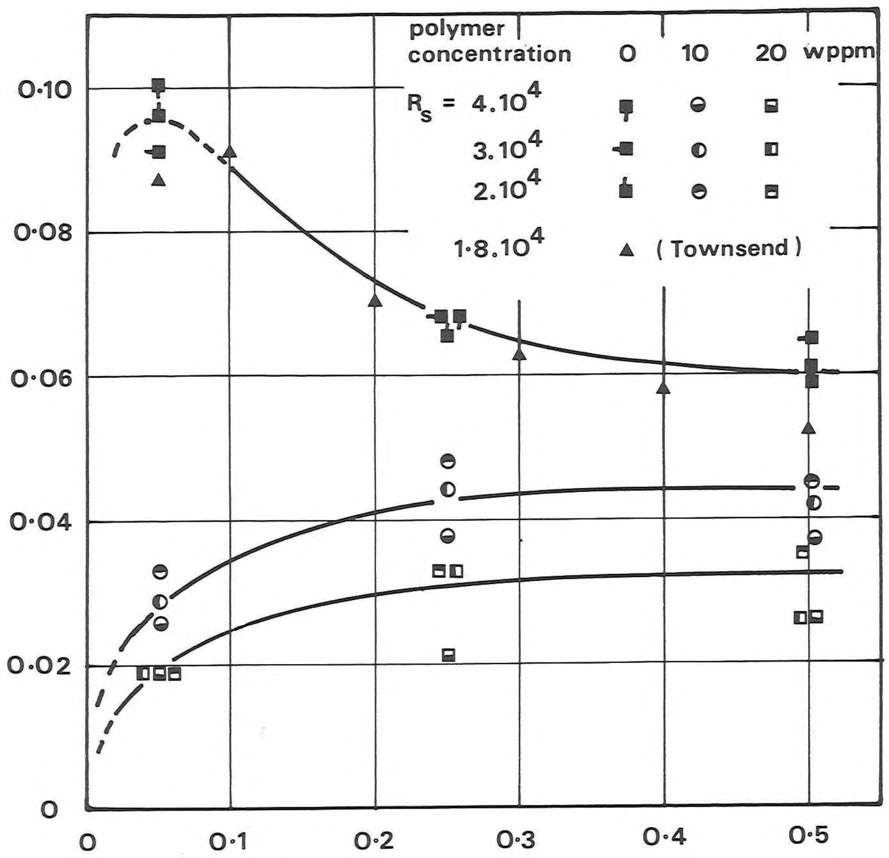


Figure 8. Variation of $\tan \frac{\overline{\theta}}{2}$ values with dye injection location across duct at different polymer concentrations. Townsend's results for water flow in an open channel shown for comparison.

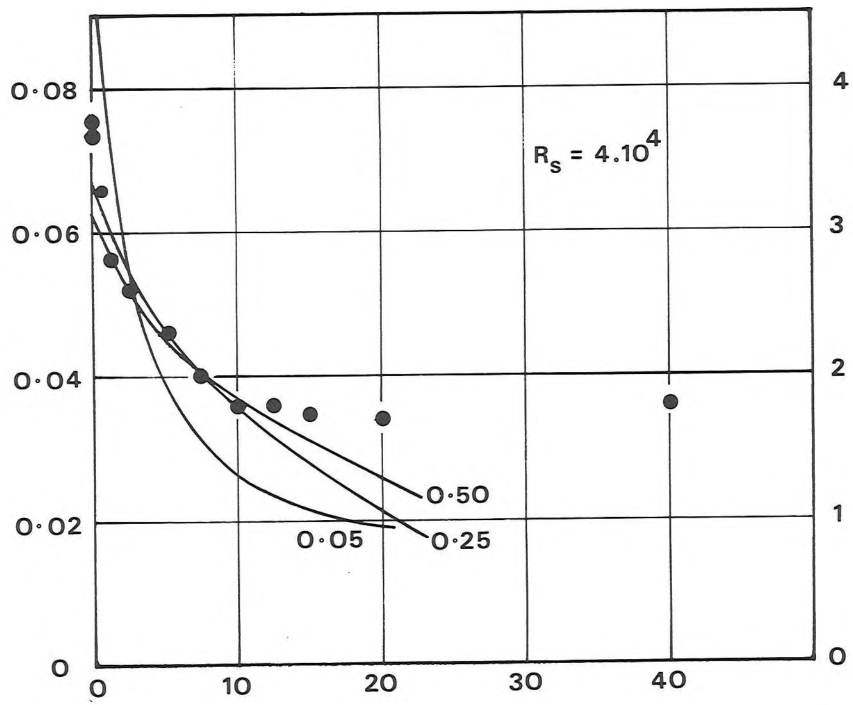


Figure 9. Comparison between head loss values ΔH (a function of drag reduction) and values of $\tan \frac{\overline{\theta}}{2}$ for different values of c. Points refer to ΔH measurements and lines to cone angles at values of y/D indicated.

ACKNOWLEDGEMENT

The author gratefully acknowledges financial support for the polymer drag reduction programme from the Department of the Environment. Thanks are due to P. Hart and P. Rimmer who developed the experimental facility and also to S. Hobbs who assisted with the experiments and the photographic work.

SYMBOLS

U_o	time-average forward velocity at a point
u	forward component of instantaneous excursion from time-average velocity at a point
v	lateral component of instantaneous excursion from time-average velocity at a point
v_{max}	maximum value of v occurring at a point during a finite time period
$\bar{\theta}$	whole cone angle measured from 1s exposure photograph of dispersing dye stream. Mean value obtained from 5 consecutive photographs
α	angular deviation of fluid particle path from mean flow direction
D	lateral internal dimension of square flow duct
y	perpendicular distance of dye release point from duct wall
R_s	solvent-based Reynolds number
c	polymer concentration in the duct flow expressed as parts per million by weight (wppm)
L	duct length from inlet to test section

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DISCUSSION

G. L. Donohue, Naval Undersea Center: About a year ago we published an article in the JFM describing some flow visualization work we did in a drag reducing flow. We injected dye through a 0.005-inch wide slot right at the wall and watched this dye collect in the low speed streaks that Prof. Kline was talking about. We did watch the bursting rate of this dye. Exactly what you stated was true. The bursting rate is greatly decreased. I think what you're seeing is similar to this. However, it's probably not quite the same thing, because you've got a probe next to the wall and I think that you may have a probe interference problem. I think it's certainly true that the bursting rates are decreased.

V. W. Goldschmidt, Purdue University: I'm not a drag reducing man, but I'm concerned by that nice periodic figure we saw there and I'm also curious then how did you inject your dye and how did you ascertain yourself that you were not looking at some transition of the dye plume itself and what was the effect of the dye injecting device? Something looks screwy. Did you measure the period of that nice orderly structure? Was it like the pulsation of the pump or something like that?

Sellin: It's very similar to the old western movie of the wagon with the wheels going backwards. Because the periodic structure was in fact a photographic phenomenon which you couldn't see before the photographs were taken. It is at 25 frames per second and in the next sequence I ran the camera at 64 frames which, when projected at 25 frames, reduced the speed of the film down to half because that shows the apparent wave length reduced by about half then. The only way I can get around this will be by going to a very high speed of film, and then running the thing at really slow motion and this should remove this effect and show that is really going on in the flow. The tendency to this periodic motion wasn't half so marked as it appeared in the film.

H. M. Nagib, Illinois Institute of Technology: There is a movie by Prof. Kline called "Flow Visualization" in which he demonstrates very beautifully the phenomena called dye injection and stability. I think that's what he called it. Now, we've done the same thing and it is very interesting. If you have a dye injection probe with variable pressure on it, you can demonstrate that you can really change this pressure and either see the true flow phenomena or some artificial phenomena coming in from the probe. As Victor Goldschmidt was saying, I think this was more probe phenomena interference than the true flow. As far as your remark about photography, we do a lot of flow visualization using movie photography and I don't think this will come in. We do it at different speed rates of the camera and when you see something, it's real.

Sellin: I appreciate your point about the dye injection velocity but it was a gravity feed from a suspended bottle and I played around with the pressure of the dye injection until I got it so that the dye stream did not appear either to expand or contract as it came out. Otherwise I made a visual matching of the dye stream velocity to the free water velocity surrounding it. The other point of course is eddy shedding of the dye support. Now this was some distance away. In terms of the probe diameter it was about 50 diameters further up stream. So I think I was out of the worst part of the probe wake but I still have to admit there may be some probe wake effect in this.

S. J. Kline, Stanford University: I was looking at the same thing and was asking myself whether it was a strobe effect or not and I don't think it is. I think that what you have is probably laminar layers on the outside of your injector probe. It looks distinctly laminar. Brown at Cal Tech has done this with Roshko a couple of years ago. In addition to the difficulty he mentions which is documented in "Flow Visualization", if you inject the dye too rapidly or too slowly you also have boundary layers on the outside of your probe inevitably. The flow is streaming off of it that way and so you have real narrow, sharp shear layers back-to-back or surrounding the thing depending on the geometry. In either case, Kaplan will show you some of the instabilities tomorrow but you get something like a Kelvin-Helmholtz instability. It looks exactly like what you're seeing and it can go a long distance downstream before it amplifies. I don't think that vitiates your results basically but I think you are seeing that in your movies.