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Aspects of the equilibrium puff in transitional pipe flow

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Flow-visualization studies in transitional pipe flow are used to reveal the mechanism responsible for the self-sustenance of a turbulent equilibrium puff. The upstream laminar fluid continuously enters the relatively-slower-moving turbulent puff around the pipe centre. The passage of this high-speed laminar plug flow past the slower fluid that resides near the wall at the upstream interface leads to the shedding of a train of three-dimensional wake-like vortices near the wall. A helical motion near the upstream interface is associated with the vortex-shedding process. The remainder of the puff is a cone of turbulence filled with these wake-like vortices that are decaying slowly; the prominent feature of the decay region is the longitudinal vortices that are apparently undergoing stretching. No toroidal vortex has been observed in the instantaneous flow field at the upstream interface of an individual puff. On the other hand, the wake-like vortices reported here have not been observed before because their three-dimensional and random nature does not allow detection by an ensemble-averaging that is not phase-referenced appropriately.

1. Introduction

In a transitional pipe flow, in the presence of a large disturbance at the entry region and at a Reynolds number Re_D of about 2250, patches of turbulence interspersed between laminar flow are observed to propagate indefinitely while preserving their length. (Re_D is based on the cross-sectional mean velocity $\overline{U}$, the pipe diameter D and the kinematic viscosity ν.) Such turbulent patches have come to be known as equilibrium puffs (Wygnanski & Champagne 1973). The fact that turbulence is continuously produced at a constant rate so that the length is maintained while the puff propagates downstream is an important aspect that makes it unique among other turbulent flows. It is obviously also of importance from the point of view of transition. There have been a very limited number of studies of this flow (Wygnanski & Champagne 1973; Wygnanski, Sokolov & Friedman 1975; also see review by Coles 1981) and it is not known what mechanism is behind the aforementioned aspects. Thus, the first question that one seeks to answer is, What is the mechanism of turbulence production that sustains an equilibrium puff indefinitely?

In the studies reported, it is largely the long-time-averaged statistical structure of the turbulence produced that has been studied experimentally. Ensemble-averaged measurements (Wygnanski *et al.* 1975; Rubin, Wygnanski & Haritonidis 1980) phase-referenced to a suitably defined trailing interface (TI) indicate that most of the turbulence is produced near the upstream laminar/turbulent interface where the flow field is dominated by a single toroidal vortex. The existence of the toroidal vortex has been inferred from the measurements of the mean streamline pattern, assuming

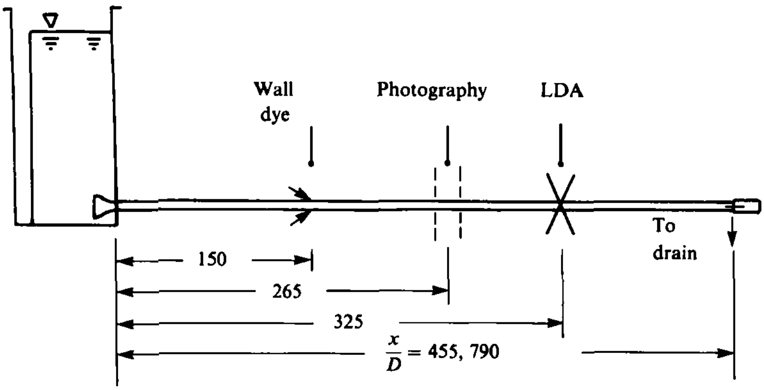

FIGURE 1. Sketch of the pipe-flow apparatus.

the time-mean flow to be axisymmetric (Coles 1981). On the other hand, if an instantaneous flow field is composed of three-dimensional organized structures which appear randomly in azimuth and time, and have not been phase-referenced individually in an appropriate manner, an ensemble-averaging is likely to lead to the smearing of useful detailed information on the structures. In a turbulence spot this had led to the smearing of information on the hairpin vortices (Perry, Lim & Teh 1981) and, as we shall show here in the case of the equilibrium puff, on wake-like vortices. It should be recognized that flow visualization has proved particularly useful in the detection of the wake-like vortices in the turbulent puff because they are three-dimensional and have considerable randomness in their temporal and spatial disposition; without any prior knowledge of their existence their detection by means of a rake of point measurements would seem to be a formidable task.

2. Apparatus and technique of flow visualization

The experiments were performed in water flowing through a straight Plexiglas circular pipe of diameter $D = 2.5$ cm resting horizontally on a table. Figure 1 shows a sketch of the apparatus. The pipe was made from 120 cm long sections joined to form a total length of $455D$ in most of the experiments and extended to $790D$ in one case. The ends of each tube section were machined and the assembly was carefully aligned to reduce azimuthal asymmetry in the flow. Measurements of the time-mean velocity profile at a higher Re_D and in the diametral plane at $x/D = 325$ by a laser-Doppler anemometer (LDA) indicated that the fully turbulent flow was axisymmetric. The entrance was located within a rectangular, Plexiglas constant-head tank, the pipe centre remaining submerged at a depth of 70 cm. The pipe entrance had an inflexional funnel with a rounded leading edge. The flow Reynolds number Re_D was adjusted by varying the flow area at the exit of the pipe. During flow visualization, the flow circuit was kept open and, at the exit, the dye and water mixture was drained away.

The large disturbance necessary to produce the puffs was provided by an orifice plate of 2 cm diameter, downstream of the funnel at the pipe entrance. Wygnanski & Champagne (1973) have shown that a disk, screen or honeycomb could also be used to provide the large disturbance at the entrance with no apparent difference in the puffs produced. Wygnanski *et al.* (1975) initiated the puffs using a single 1 mm diameter jet produced by a speaker and emanating from the wall at the entrance.

More recently, Rubin *et al.* (1980) have used a pair of 2 mm diameter jets instead. They have further shown that the puffs are produced just as well when the disturbances are applied on the fully developed Poiseuille flow instead of at the entrance. As we shall see later, the puff is independent of the type of device that produces the disturbance and, largely, its streamwise location simply because the prime requirement to initiate the production of turbulence downstream is a laminar-to-turbulent interface with a large velocity drop across it.

The importance of regulating the cross-sectional mean flow in a pipe-flow experiment on transition, where the flow is intermittently laminar and turbulent, has been recognized by many (see Coles 1981 for example). Unless care is taken, the flow could be self-regulating and it would be difficult to reproduce the results accurately in a different facility. In the present flow circuit, any large variation in the mass-flow rate during the periods of laminar and turbulent flows was minimized by the large disturbance produced by the orifice plate at the entry and the severe throttling provided at the pipe exit.

The reproducibility of the present experiments was ensured by producing the characteristic puff velocity signature at the centreline by the LDA and also by visually observing that the two qualitative aspects of the instability near the upstream interface, viz the velocity mismatch and the development of a helical motion, remained persistent from an x/D of 265 to 790. Further checks were provided by the measurements of Stettler & Hussain (1982) who also used this facility to study the effect of pulsation on transition due to large disturbances at the entry. They detected the puffs by an LDA system at $x/D = 320$. The steady flow was found to be fully developed. The frequency f_p was obtained by averaging over about 40 minutes. For a steady flow, excellent agreement was obtained with the linear distribution of puff frequency $F_p(f_p D/\overline{U})$, measured by Wygnanski & Champagne (1973) for $2000 \leqslant Re_D \leqslant 2350$. Note that Wygnanski & Champagne have also shown that between $2000 \leqslant Re_D \leqslant 2700$ both the puff frequency and intermittency do not change for $x/D > 100$; apparently 'for $x/D > 100$ the average puff reaches some kind of moving equilibrium with its surrounding flow'. Thus it was concluded that the puffs photographed at $x/D = 265$ were independent of x/D.

Ordinary tap water was used as the flow medium. A soluble greenish-yellow dye called Uranamine was used for flow visualization. It fluoresces in laser light. The dye was diluted with water before use and its density was nearly equal to that of water. The Schmidt number of the dye was about 10^3. This high ratio of the two molecular-diffusion-rate coefficients ensured that the dye marked the eddies with high fidelity. That this was the case was checked in the following manner. The puffs could also be identified by their characteristic centreline total U-velocity time-signature (see figure 2 of Wygnanski *et al.* 1975 for an example). Three distinct features appeared with time. First, over the greater part of the downstream region, a gradual and eventually large drop in the quasi-laminar velocity took place. This was followed by the somewhat sudden appearance of large turbulent fluctuations that resided largely over a narrow region near the upstream interface. Thereafter, the velocity abruptly returned to the laminar level prevailing upstream of the puff. This signature was obtained by the single-channel LDA placed at the centreline at an x/D of 325. Since the flow velocity was low, it was also possible to observe visually the dye-marked puffs in the normal room lighting as they moved down the pipe. This turned out to be useful in itself, but also allowed us to verify whether the puffs identified by the LDA signature coincided with those marked by the dye. This was achieved by simply comparing simultaneously the characteristic U-signature of the puff centreline as captured by the LDA on a storage oscilloscope with the passage of the dye-marked puff past the LDA station. Note that the station of LDA measurement was located beyond that where photography was normally performed. In contrast to the problem of detection of a coherent structure in a fully turbulent environment, making the above simultaneous comparison was not difficult because the puffs were interspersed in laminar-like fluid.

The dye was injected slightly tangentially into the pipe through a pair of flush-mounted stainless-steel tubes of diameter 0.7 mm spaced diametrically opposite to each other at $x/D = 150$. Similar injection tubes were also mounted in the funnel and immediately downstream of the orifice plate to explore a suitable location to mark the puffs. However, they could not be used because, far downstream, the turbulent diffusion had lowered the concentration level significantly. A small tank plumbed to the injection tubes was filled with the diluted dye. The local static pressure was monitored and the head in this tank was kept just above this pressure. This ensured that the issuing jets did not disturb the laminar flow in the pipe. The issuing wall dye was also observed to contain no oscillation or ring vortex and it remained distinct because of slow laminar dispersion during the intervals between the appearance of the puffs. Two of the injection tubes were mounted in the horizontal plane and two in the vertical to permit photography in these planes. There was no noticeable difference in the pictures taken in these two planes. The injection rate of the diluted dye was negligible compared with the flow rate through the pipe. The dye line first marked part of the laminar pipe flow and resided largely near the wall. Later on, in the puff it marked approximately the turbulent vorticity distribution resuting from the laminar-flow breakdown.

A longitudinal cross-section of the pipe in the diametral plane was illuminated by a thin sheet of light. The light source was a 0.75 W argon-ion laser. The laser beam was fanned into an approximately 1 mm thick sheet by means of a small diameter (a few mm) cylindrical glass rod and trimmed. A pipe length of about 20 cm was illuminated. The technique of flow visualization was essentially similar to that used by Head & Bandyopadhyay (1981).

Photography was performed using a 16 mm cine camera run at about 100 frames/s with colour film. The rated ASA number of 400 was stretched to 1000 during development. Short-exposure still shots using a 35 mm camera fitted with a 70 mm macro lens were also taken in both diffused room and sectional laser illumination. The photography reported here was done at $x/D = 265$. Since the dye was injected at about 2.9 m upstream of this station, it allowed us first to mark the laminar plug immediately upstream of the puff trailing interface. Thereby it was possible to visually identify and then photograph only those puffs in which the penetration of the laminar plug across the trailing interface of the puff and its subsequent breakdown into turbulence took place within the field of view. This breakdown was unmistakable because it involved a sudden and vigorous helical motion, and formation of discrete eddies.

Because of attenuated contrast in a photograph, identifying a coherent large structure in the fully turbulent region of the puff can be difficult. Also, the typical size of these structures, which is of the order of the pipe radius, is small in our case. The combination of a closed-circuit video system using variable magnification and video edge enhancement was found useful.† The enhancement circuit electronically treats the video signal to reduce the overall contrast in the frame but increases it

† Dr L. Weinstein of Langley Research Center is thanked for helping with the picture enhancement.

over local areas (edge enhancement). The phase shift in filtering gives it a relief effect which further aids the visual examination of the structures. This enhancement is a video version of a photographic technique developed for conventional photography by Weinstein & Fitzer (1975).

There are limitations both in the techniques of point measurement, such as hot-wire or laser-Doppler anemometry, and in flow visualization. In recent experimental turbulence research, flow visualization is finding increasing use, and the necessity of exercising caution in the interpretation of flow-visualization pictures in flows that vary in space and time has been stressed by several investigators over the years (see, for example, Hama 1962; Maxworthy 1972; Merzkirch 1974; Kline 1978; and Head & Bandyopadhyay 1981). There are several problems that should be considered. While the pictures give us the streaklines, the mean streamlines or pathlines are also desirable because of their amenability to mathematical treatment; however, this is a difficult task. In what is a rare example of analytical treatment Hama (1962) has demonstrated that the rolling-up of streaklines cannot be taken as positive evidence of the presence of discrete vortices. This risk is often minimized by the simultaneous use of flow visualization and anemometry. Maxworthy (1972) in his study on vortex rings has inferred that the vorticity remained distributed over regions beyond those marked by the dye. Head & Bandyopadhyay (1981) have pointed out that, on the one hand, there may be mean or fluctuating vorticity beyond the edge of the smoke-marked region because the transfer of vorticity on a molecular scale is more efficient than that of oil droplets. On the other hand, since although vorticities of opposite sign could cancel each other, there is no similar mechanism that can reduce the concentration of smoke. However, in a turbulent environment it is likely that vorticities in all directions will not get cancelled simultaneously and thus the tracer will not give a wholly misleading picture. Therefore, one should refrain from positively identifying the dye interface as also the turbulent/non-turbulent interface.

In response to questions raised by Klebanoff about studies on forced transition in boundary layers by a circular rod, Perry *et al.* (1981) have shown by simultaneous hot-wire measurements and smoke-flow visualization that the smoke filaments could indeed be identified with regions of concentrated vorticity. Using a similar technique, Bandyopadhyay (1978) has also studied the three downstream regions of this flow field where the vortex lines are respectively periodic, quasi-periodic and random in time. The Reynolds number based on the free-stream velocity and the rod diameter varied from 127 to 166. The visualized rotational flow field and the u-velocity fluctuations at three points across the shear layer have been simultaneously photographed and recorded on magnetic tapes and a storage oscilloscope located within the field of view (see Head & Bandyopadhyay 1981 for a description of this technique). It has been found that the typical velocity signature of a vortex is produced when a hairpin-shaped smoke filament passes by. This shows that, close to the region of formation of the discrete vortices, the smoke filament could be identified with regions of concentrated vorticity. Matsui (1981) has also made a similar satisfactory comparison between a hot-wire velocity signal and the smoke-marked wake vortices shed behind a circular rod. Finally, the intermittency measurements of Fiedler & Head (1966) in a turbulent boundary layer have shown that the instantaneous smoke-filled region could be closely identified with the turbulent field.

3. Results and discussion

The results presented in this section describe some of the new qualitative dynamic features of the puff that have been identified. The 'motor' that is driving the puff lies in its upstream region; the puff is 'fuelled' by the laminar flow that exists upstream and the formation of discrete organized vortices from the laminar flow (the motor) takes place over an extended length of several x/D. The flow in this region develops a streamwise helical motion that is spread over most of the pipe cross-section. The motor could be said to be 'started' by the velocity mismatch that perennially exists between the high-velocity laminar plug prevailing around the pipe centre and the slow-moving turbulent fluid residing near the wall in the upstream region of the puff. Since such a mismatch would always exist between a turbulent and a laminar region, it is immaterial how the disturbance is produced and whether it is introduced into the region of developing or fully developed laminar pipe flow. The organized vortices formed are found to be three-dimensional wake-like vortices. They populate the fully turbulent region while undergoing stretching and dissipation. The toroidal vortices have not been observed in the instantaneous flow field of the individual puffs and the early stages of breakdown is found to be three-dimensional. In §3.1 the preliminary observations of the velocity mismatch and the existence of a streamwise helical motion near the upstream interface are discussed. In §3.2 the differences between the detailed structure of the instantaneous flow field near the upstream interface in the individual puffs and the structure of the averaged flow field inferred from an ensemble of puffs phase-referenced to the upstream interface, are introduced. The feasibility of the formation of toroidal vortices in a pipe flow in general is examined in §3.3 and in §3.4, the observations on the wake-like vortices are presented. Finally, in §3.5, the present observations are compared with the flow-visualization results of Reynolds (1883).

3.1. *Preliminary observations*

Owing to the low flow speeds, the general outline of the puff could be followed with the naked eye in the normal diffused room lighting as it moved downstream. Since the puff is an energetic turbulent entity, its upstream region is clearly identified by the swirling dye streaks which are otherwise rectilinear in the far-upstream laminar region preceding the puff. To test if the puffs under examination indeed survived indefinitely, the length of the pipe was increased from $455D$ to $790D$, which happened to be the end of the laboratory. The location of dye injection and the inlet orifice were left undisturbed. The helical overturning motion at the trailing interface of the puffs were found to continue to the end of the pipe although the dilution of the dye prevented us from ascertaining whether the length of the puff was preserved. No splitting or merging of puffs was observed to take place. This suggests that those puffs were in a state of near-equilibrium.

Preliminary observations revealed that, around the pipe centre, the upstream laminar fluid was moving at a much higher speed than the upstream turbulent region of the puff. Figure 2 shows a sequence of frames from a cine film, taken later with the sectional light plane, showing this mismatch of velocity near the upstream interface. In the figure, the radial location and the tip of the laminar dye line are marked by thin arrows. The streamwise location of a blob of turbulence near the wall has been marked by a thick arrow. This velocity mismatch must have been substantial for it to be so obvious and to make the laminar fluid enter continuously into the relatively slower-moving turbulence in the puff. This penetration of the

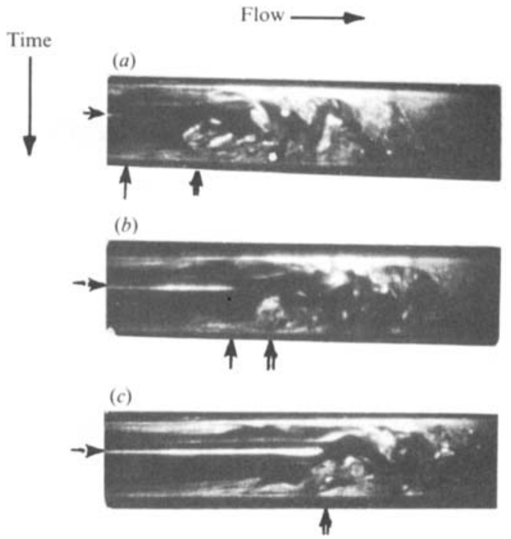

FIGURE 2. Sequence of frames showing the velocity mismatch between the fast-moving laminar plug around the pipe centre near the trailing interface of a puff (marked by pairs of thin arrows) and slow moving fluid near the wall (thick arrow).

upstream interface took place in every puff. It was suspected that the velocity mismatch was related to the fact that the streamwise velocity profile is more pointed around the pipe centre in a Hagen–Poiseuille flow than that in a turbulent flow; for example, Nikuradse's (1949) measurements in a 1 cm diameter pipe at a low Re_D of 4000 show that the difference between the laminar and time-mean fully turbulent velocity at the centreline is 0.77 times the cross-sectional mean velocity. In reality, of course, the mismatch of velocity would be spread over a length determined by the processes of instability. The flow upstream of the puff interface now assumes considerable importance. A high-velocity plug can also be seen in Wygnanski *et al.*'s (1975, cf. figure 11) ensemble-averaged measurements of mean-velocity distributions across various upstream sections in the puff, phase-referenced to a suitably defined trailing interface. These measurements show that at a streamwise distance of $0.6D$ upstream of the interface at the centreline ($(x_{\mathrm{TI}}/D)_{\mathrm{CL}} = 0$), the plug is well developed, has a diameter of about $\frac{1}{2}D$ and the velocity rises by about 70 % over a radial distance of only about $0.1D$. In their figure, it is also of interest to note that the velocity profile is inflexional over a length of about $4D$ in the region upstream of the interface at the centreline and that the point of inflexion moves toward the pipe centre as $(x_{\mathrm{TI}}/D)_{\mathrm{CL}} = 0$ is approached; furthermore, the fluid between the region of inflexion and the wall is turbulent over this length, the local c_f remaining virtually at the same turbulent level. To summarize, upstream of the puff trailing interface at the pipe centreline, there exists a high-speed laminar plug around the pipe centre and a region of slow-moving fluid near the wall with a thin region of inflexion in the mean-velocity profile lying in between.

During the preliminary observations, another aspect of the flow near the trailing interface appeared prominently. In the diffused room lighting, it was observed that the dye streaks, when present around the pipe centre and in the laminar plug close to the upstream side of the trailing interface of the puff, exhibited a helical motion that appeared suddenly. Figure 3 shows an example photographed in the normal room

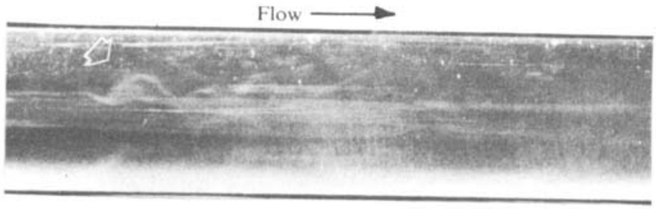

FIGURE 3. Helical motion in the laminar plug as seen in general room lighting.

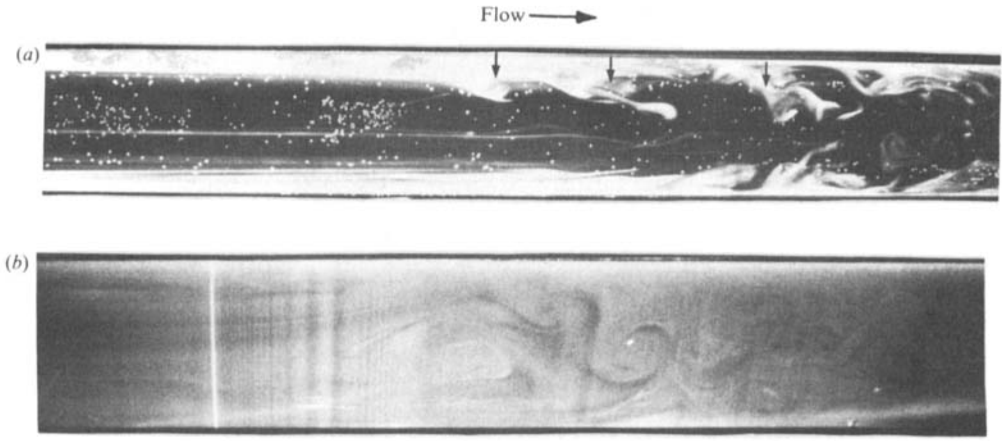

FIGURE 4. Helical motion in the laminar plug as seen in sectional lighting.

lighting. It is a view of the dye integrated along the line of sight. Thus the early part of the helical motion is clear but the details of the eddying motion that followed are smeared. Figures 4(*a*, *b*) show the helical motion in the sectional laser illumination. The figures show that the impinging part of the laminar plug is experiencing a longitudinal helical motion which extends over a large part of the pipe cross-section. Note that, in the region further upstream, there is no obvious azimuthal motion. Also, the appearance of the helical motion coincides with the rolling up of the dye at one diametral end of the pipe into what appears to be a discrete three-dimensional vortex. This aspect will be discussed further in §3.4.

A phenomenon has been observed occasionally that is worthy of mention. Figure 5 contains a sequence of frames from a cine film showing the appearance and disappearance of an 'island' of rolled-up dye around the pipe centre near the upstream interface of the puff. The lack of axisymmetry in the structure of the instantaneous flow field is clear. The appearance of the 'island' could be explained once we recognize that a jet-like motion perpendicular to the plane of view, and along the diameter, is taking place. Figure 6 contains a similar sequence of frames also showing a jet-like motion diagonally across the pipe but this time in the plane of observation. These are compatible with a helical motion across the pipe.

The 'sudden' appearance of the helical motion can be explained by considering the effect of an axisymmetric contraction on a stream of fluid rotating in a pipe (Batchelor 1970). Consider a vortex line that is straight and parallel to the axis of the pipe and rotating about it. As it encounters a contraction, the reduction of its distance from the pipe axis would lead to a corresponding increase in its azimuthal velocity, since their product has to remain constant. This would lead to a deformation of the vortex

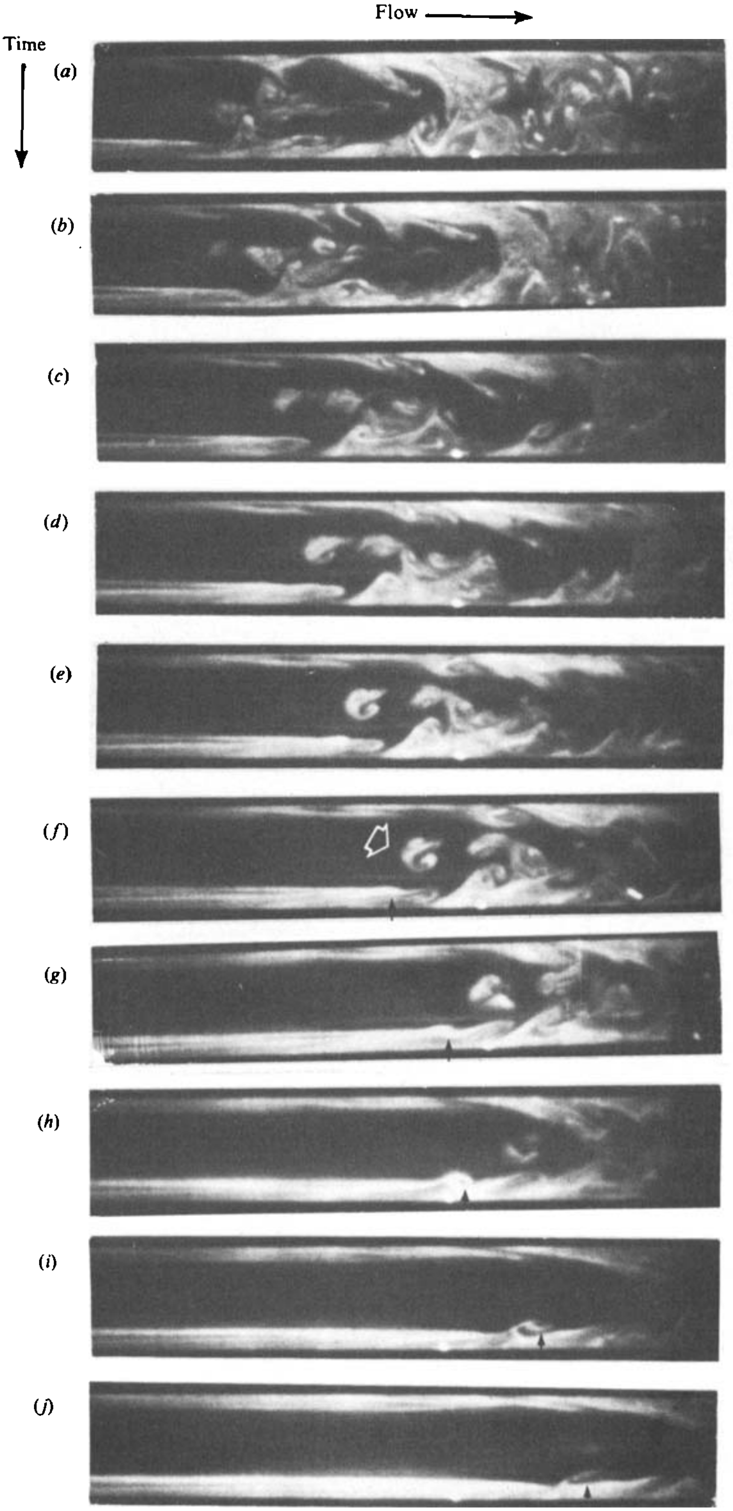

FIGURE 5. Sequence of frames showing the appearance of an island near the pipe centre in the neighbourhood of the trailing interface of a puff. Note the growth of the dye roll-up near the wall.

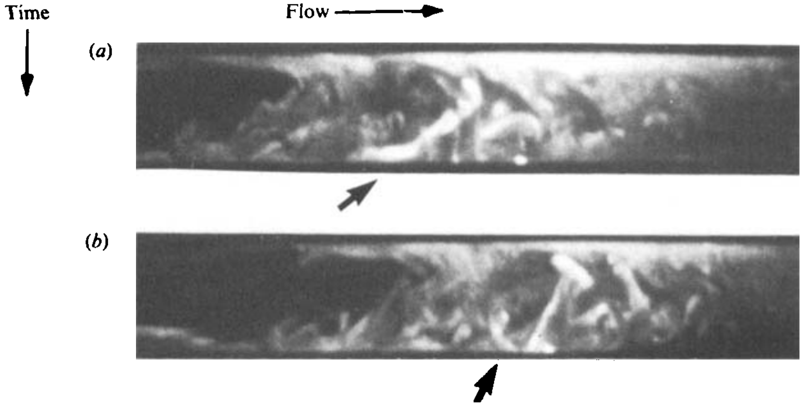

FIGURE 6. Sequence of frames showing a jet-like motion diagonally across the pipe.

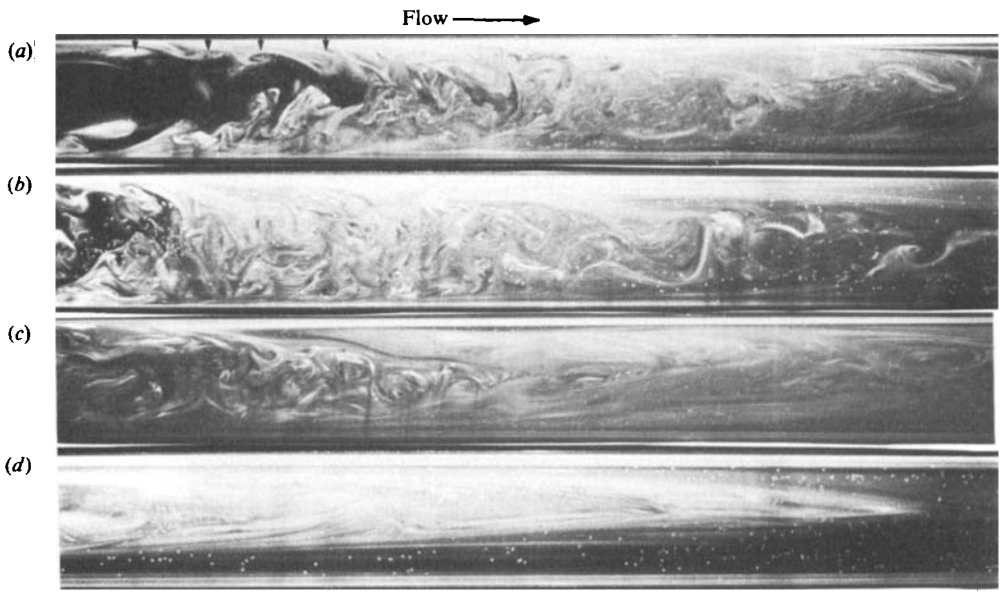

FIGURE 7. Puff structure. Note the resulting cone of turbulence. (*a*) and (*b*) are in the upstream region; (*d*) is in the far downstream region and (*c*) is in the intermediate region.

line into a helix, the sign being the same as that of the axial vorticity in the far-upstream region. Quite long-exposure visualization pictures had clearly showed that, at the trailing interface of the puff, which is conical in shape, as far as the laminar plug is concerned, the slow-moving fluid near the wall had virtually formed a contraction. Thus, even a small rotational motion prevailing in the laminar flow far upstream of the puff is likely to change to a helical motion as it encounters the contracting effect of the trailing interface of the puff.

A preliminary overview of the wide variety of dynamics prevailing in the various regions within the puff is depicted in figures 7(*a*–*d*). The puffs can be divided into three regimes. The first is the conical laminar-to-turbulent interface at the upstream end, shown in figure 7(*a*). It extends over $3D$ to $4D$. The interface is corrugated and characterized by near-wall quasi-periodic vortex roll-ups (marked by arrows) which

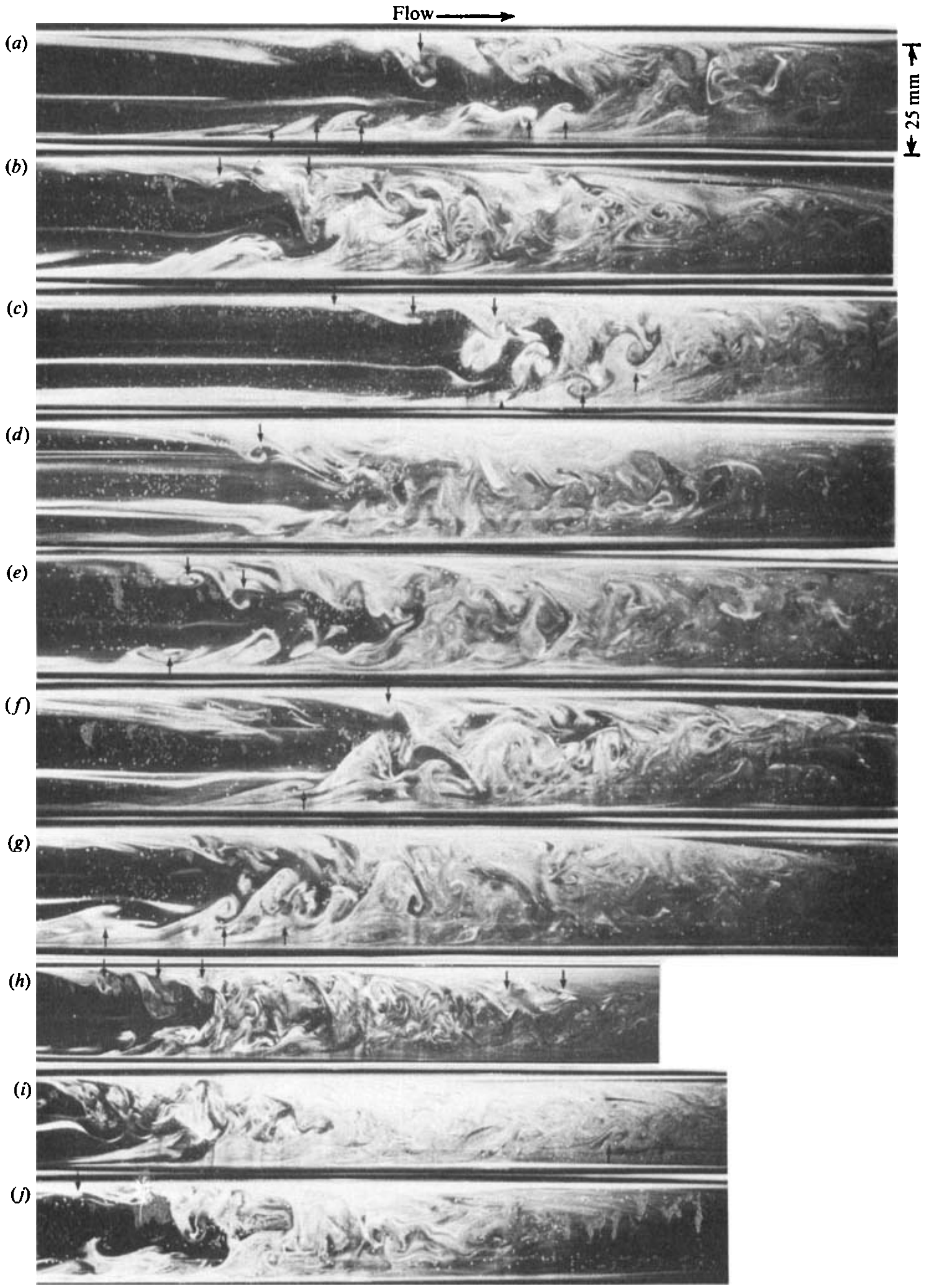

FIGURE 8. Puff structure in the upstream region.

presumably pertain to the nonlinear stages of the instability process. The last five frames in figure 5 show the time sequence of the beginning of such a vortex roll-up near the wall. This would appear as a 'spike' in the velocity signal (see the examples of isolated velocity 'spikes' near the wall in figure 5 of Wygnanski & Champagne 1973). This region is followed by a fully turbulent region extending over about $5D$,

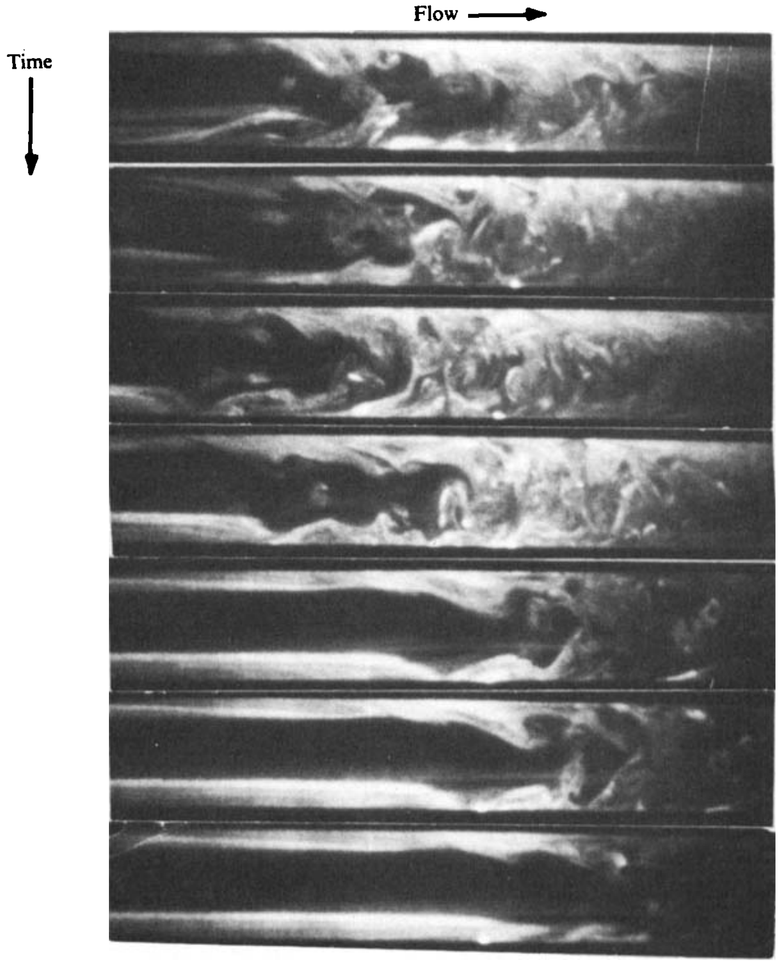

FIGURE 9. Sequence of frames showing the persistence of the laminar plug and repeated breakdown into turbulence near the upstream interface of the puff.

shown in figure 7 (*b*). In the cine films this region is found to be very active. The helical motion can be observed in both of the above regions. The third region of the puff is conical, and is the largest. It is shown in figures 7 (*c*, *d*). This is the so-called 'relaminarizing' region and the downstream laminar-to-turbulent interface is not well defined. The helical motion does not persist to this region and the cine films show very little overturning motion here.

3.2. *The structures of the instantaneous and ensemble-averaged flow fields*

How does the structure of the instantaneous flow field in the individual puffs compare with the structure of the averaged flow field inferred from an ensemble of puffs phase-referenced to their trailing interfaces? The structure of the individual puffs is unknown and there has not been any flow visualization or hot-wire study of it. On the other hand, the structure of the averaged flow field is known to be a toroidal vortex residing near the trailing interface.

In the early stages of this work, and in the absence of any guideline, it was assumed that a toroidal vortex exists in the upstream region of the instantaneous flow field

(a)

(b)

(c)

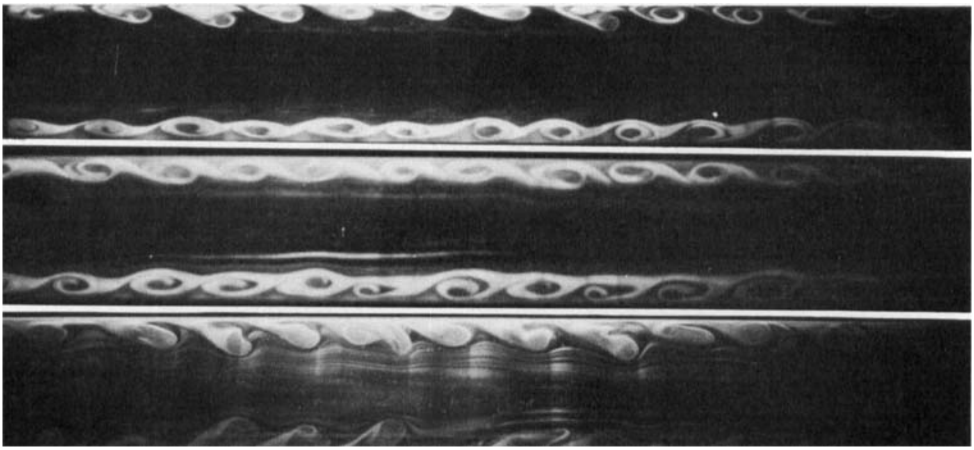

FIGURE 10. Kelvin–Helmholtz-like vortex rollups in a pipe. Normal flow direction is from left to right.

of the individual puffs as it does in the ensemble-averaged flow field. Thus, a hypothesis was developed proposing that the passage of the aforementioned high-speed laminar plug past the trailing interface led to a roll-up of vorticity in much the same way as in an axisymmetric mixing layer (Bandyopadhyay & Hussain 1983). To make a provision for the turbulence in the puff, it was suggested that the roll-ups undergo a chaotic breakdown into turbulence followed by a relatively long region of decay and 'relaminarization'. As a start, this would seem to be an adequate hypothesis that explains the mechanism of self-sustenance.

The short-exposure single shots and cine films of the longitudinal cross-section of the puff were then examined to see if the hypothesis could be substantiated. This gave rise to several questions. First, figure 8, which is a random collection of examples of longitudinal sections through the puffs, shows that the upstream region of the puff does not usually have a pair of symmetric vortex roll-ups across the centreline that could be taken as the sections of a toroidal vortex. In the cine films, the roll-ups at the two diametrical ends appeared to be uncorrelated. Secondly, the existence of the helical motion casts doubt on the rolling up of a vortex sheet that is axisymmetric about the centreline; in fact, a roll-up that is azimuthally asymmetric would seem to be more appropriate. Thirdly, in the upstream turbulent region of the puff, there was no obvious sign of any motion that could be indicative of a sudden break-up of the toroidal vortex due to any azimuthal instability. Fourthly, the sections of the organized turbulent structures detected in the turbulent region of the puff were not like mushroom or ring vortices that have a pair of symmetric roll-ups. Finally, at the trailing interface, usually there existed not one vortex roll-up but several that formed an approximate train in spacing and orientation (suggesting the existence of an underlying quasi-periodicity), the roll-ups taking place over a length of several diameters (figures 4*a*, 8(*a*, *c*, *g*), 9 and 12).

There are other associated questions that also need to be considered. The toroidal vortex under scrutiny can at best be considered to be a laminar roll-up and not a 'truly' turbulent large structure. If smaller ring vortices are indeed formed out of the break-up of this toroidal vortex they would still be only two-dimensional. The mechanism of vorticity production and stretching would be difficult to explain in the

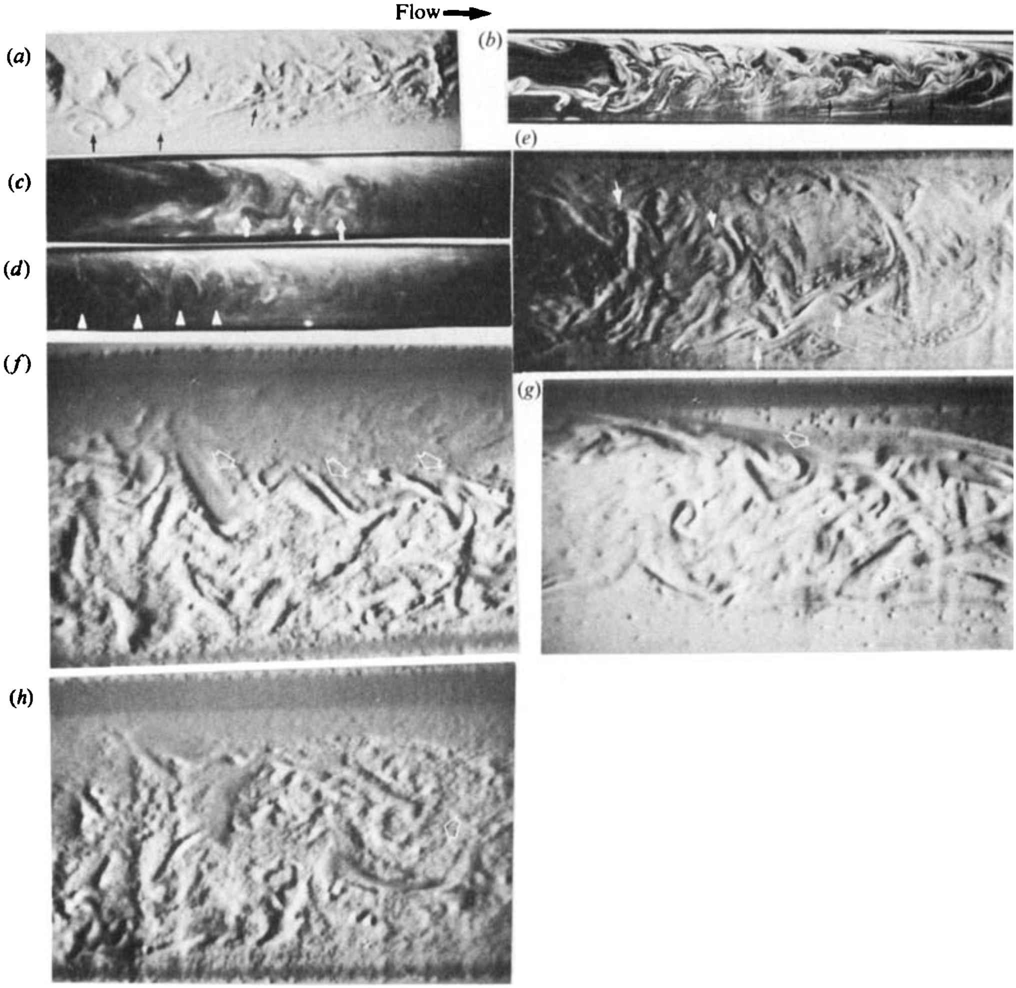

FIGURE 11. Wake-like vortices in the turbulent region of the puff.

context of our flow (Tsinober & Levich 1983; and Moiseev *et al.* 1983). If an axisymmetric roll-up is indeed taking place near the upstream interface the effect of the wall proximity would be to act like a brake. The formation of many structures successively along the pipe length would be unlikely.

Thus, it is concluded that there is no toroidal vortex near the trailing interface of the individual puffs. The toroidal vortex can be seen to be the result of the ensemble-averaging operation performed on the puffs, without any regard for the phase of the three-dimensional vortex roll-ups taking place in the individual puffs, smearing the details in the process. These details of the structures are further discussed in §3.4.

3.3. *Kelvin–Helmholtz-like roll-ups in a pipe*

In the preceding section the feasibility of a vortex sheet rolling up axisymmetrically in the upstream region of a puff, as examined in the instantaneous flow field, has been discussed. In a different vein one asks, Is it possible to have Kelvin–Helmholtz-like

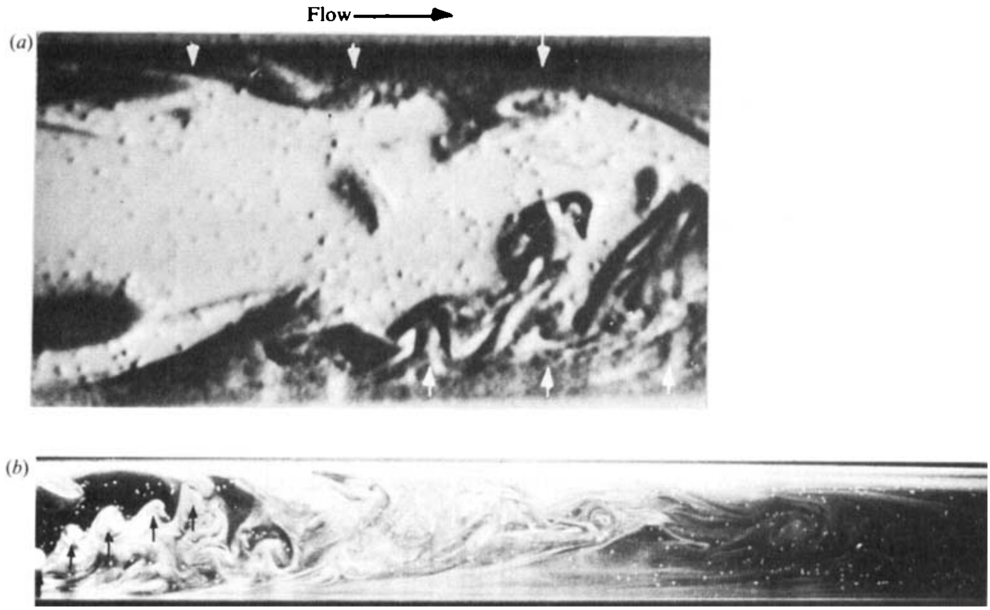

FIGURE 12. Growth of wake-like vortices at the trailing interface of the puff.

roll-ups in a pipe? Although there is no reason why it should not, to the author's knowledge this has not been demonstrated yet.

To test this, the pipe flow described earlier was set to run near the lower critical Reynolds number, $Re_D = 2000$. A bypass valve also of diameter D that usually stayed closed, located near the normal exit, was manually fully opened quickly and shut immediately thereafter. Since the normal exit area was much smaller compared with that in the valve, the above sequence produced a large acceleration followed by a deceleration that nearly brought the pipe flow to a halt for a fraction of a second. The longitudinal plane of light at the normal station of photography revealed that the length of pipe under observation had become filled with a train of nearly equi-spaced and identical ring vortices. It is possible that the roll-ups existed beyond the field of view as well. Figures 10(*a–c*) show three examples. These are quite representative because the degree of organization shown here could be reproduced in almost every cycle. The dye roll-ups appeared to take place locally. The train of ring vortices stayed in this highly organized state for only a fraction of a second. Soon afterwards, these laminar roll-ups quickly grew in size locally while exhibiting virtually no streamwise convection, and then chaos ensued as the pipe flow was re-established. Measurements of the instability process have not been made because they did not seem relevant. But it is believed that the results suggest that a Kelvin–Helmholtz-like roll-up of laminar vorticity could in principle occur in a pipe flow. Of course, as far as the puff is concerned, such organized axisymmetric laminar roll-ups have not been observed in the instantaneous flow field of the individual puffs.

3.4. *Wake-like vortices*

The technique of picture enhancement became available at this stage and the short-time-exposure single shots and cine films were re-examined. Figures 11 (*a–h*) show examples of sections through many discrete vortex roll-ups. In figures 11 (*a*), (*d*)

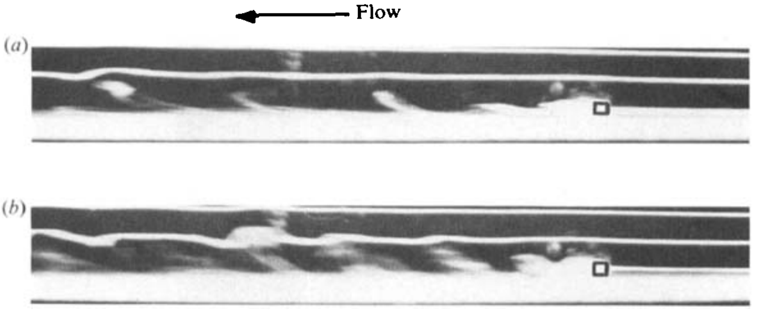

FIGURE 13. Vortex shedding behind a three-dimensional obstacle. The obstacle is a 1:12000 model of Ferry Bridge cooling tower in the UK. Free-stream velocity is higher in (*b*).

and (*f*), organized trains can be discerned. Generally speaking, in the fully turbulent region of the puff shown in figure 11, the individual vortex roll-ups can be recognized but their sequential nature is not obvious. However, this could be identified better during their formation at the trailing interface of the puffs. They are marked in figures 4(*a*), 7(*a*), 8(*a*, *c*, *e–h*) and 12(*a*, *b*).

The smoke pattern of the periodic wake vortices formed behind a three-dimensional obstacle resting on a surface in a laminar boundary layer is shown in figures 13(*a*, *b*). (The obstacle in this case is a 1:12000 model of the Ferry Bridge cooling tower in the UK that collapsed apparently owing to flow-induced vibration). The free-stream velocity is higher in figure 13(*b*) than that in 13(*a*). As shown in figure 10 of Perry, Lim & Chong (1980), the smoke pattern in figure 13(*a*) is similar to that of the wake vortices shed behind a rivet head resting on a surface, at a Reynolds number of 150 (based on the maximum height of the rivet head). The quasi-periodic dye patterns marked in figures 4, 7, 8 and 12 compare well with those of the wake vortices shown here in figures 13(*a*, *b*) and in figure 10 of Perry *et al.* (1980) (see also Zdrakovich 1969).

Following this, we assume that a wake Reynolds number of 150 is representative of the vortex shedding at the trailing interface of the puff. It has been shown earlier that the laminar plug at the puff trailing interface has an excess velocity (U_c) of about $0.7\bar{U}$ compared to the near-wall region. This gives a maximum 'obstacle' height Δ of about $0.1D$ which is a physically reasonable value. Using this, the Strouhal number $St\,(f\Delta/U_c)$ of the dye patterns marked in figures 4(*a*), 8(*a*, *c*, *e*), 12(*a*, *b*) are respectively 0.15, 0.24, 0.19, 0.24, 0.29 and 0.34. Furuya & Miyata (1972) have measured the Strouhal number of wake vortices shed behind spheres and cylinders of aspect ratios of 1–28 (axis lying along span) resting on a surface and lying within a laminar boundary layer; below a Reynolds number ($U_c\,\Delta/\nu$) of 250, St varied from 0.15 to 0.3. Sato & Onda (1980) have reported that the Strouhal number behind cones resting on a surface vary from 0.2 to 0.35 as the ratio of diameter to height is increased from 0 to 3.5. We conclude that our estimates of the Strouhal numbers of the vortex shedding at the trailing interface of the puff compare reasonably well with those measured behind three-dimensional obstacles resting on a surface. The high anisotropy observed upstream of a puff (Wygnanski *et al.* 1975) can be attributed to these wake-like vortices. Here, the three-dimensional nature of the roll-up of the vortex sheet and the streamline pattern are envisaged to be similar to those deduced by Perry *et al.* (1980) for a 'single-sided' wake. Phase-averaged measurements are required to establish how close these vortices are to wake vortices; but we believe that the above demonstrates their quasi-periodic nature.

Figures 11 (*f–h*) show a few examples of cross-sections of the wake-like vortices within the turbulent cone of the decay region of the puff. The vortices are three-dimensional, turbulent and their topological features, namely the focus and saddle, are evident. This region of the puff is known to be both a region of flow acceleration and decay of turbulence. The vortex stretching that is going on in the saddles could contribute to the decay of turbulence by intensifying the vorticity distribution. The enhanced pictures (figure 11) and figures 7 and 8 show that the decaying part of the puff is characterized by relatively straight strands (also see Cantwell & Coles 1983). In this decay region, the foci have become smaller and the strands longer compared with those prevailing further upstream. Thereby, in the cine films, the strands dominate the area being viewed and the overturning motion appears much weaker in the longitudinal plane of the decay region. The topology of the vortex suggests that stretching is taking place within the strands. Owing to the tendency of the strands to appear in pairs, we conjecture that these are also counterrotating vortices like those in the wall region of a boundary layer. The likelihood of turbulence production due to stretching in the longitudinal strands in the downstream region of the puff suggests that caution has to be exercised in characterizing the flow as relaminarizing. These vortices are longitudinal and, therefore, have a long lifetime. This seems to explain why the final decay region of the puff is the largest.

3.5. *The experiments of Reynolds*

Visualization was used most extensively by Reynolds (1883) in his experiments on flow through a pipe. This led to the discovery of what is now known as the critical Reynolds number. Two such numbers were found. The lower and upper critical Reynolds numbers of about 2400 and 15270 were obtained for large and small disturbances respectively. This shows that the flow has a strongly nonlinear character (Orszag & Patera 1981). The lower limit is now commonly taken to be about 2000 whereas various upper limits can presumably be reached depending on the care taken to minimize the disturbances.

Reynolds also used flow visualization to study the details of the fluid motion during transition. Two phenomena were observed. First

> Where there was any considerable disturbance in the water tank and the cock was opened very gradually, the state of disturbance would first show itself by the wavering about of the colour band in the tube; sometimes it would be driven against the glass and would spread out, and all without a symptom of eddies. Then, as the velocity increased but was comparatively small, *eddies, and often very regular eddies,* [present author's italics] would show themselves along the latter part of the tube. On further opening the cock these eddies would disappear and the colour band would become fixed and steady right through the tube, which condition it would maintain until the velocity reached its normal critical value, and then the eddies would appear suddenly as before.

The second was the intermittent character of the transition process irrespective of whether the inlet disturbance was small or large; often, patches of 'disturbance' would appear quasi-periodically.

Consider some additional description of the flow visualization by Reynolds (1883).

> The colour was allowed to flow very slowly, and the cock slightly opened. The colour band established itself much as before, and remained beautifully steady as the

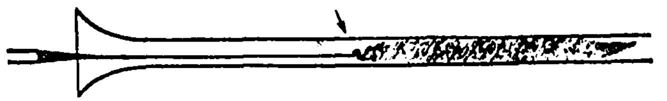

FIGURE 14. Figure 4 of Reynolds (1883) showing coloured cloud.

FIGURE 15. Figure 5 of Reynolds (1883); spark photograph of coloured cloud.

velocity was increased until, all at once, on a slight further opening of the valve, at a point about two feet from the iron pipe, the colour band appeared to expand and mix with the water so as to fill the remainder of the pipe with a coloured cloud, of what appeared at first to be a uniform tint [figure 14]. Closer inspection, however, showed the nature of this cloud. By moving the eye so as to follow the motion of the water, the expansion of the colour band resolved itself into a well defined waving motion of the band, at first sight without other disturbance, ***but after two or three waves came a succession of well defined and distinct eddies***. [present author's italics]. These were sufficiently recognizable by following them with the eye, but more distinctly seen by a flash from a spark, when they appeared as [...in figure 15].

One cannot help noticing that the dye patterns shown in figures 3 and 4, taken in the room and sectional lighting respectively, bear striking similarities to the 'waving motion' and 'distinct eddies' shown in figures 14 and 15 respectively.

Reynolds' description of the organized nature of the transitional pipe flow appears to have got buried under time. An exact duplication of his apparatus and rerun of the experiments seem warranted to understand the detailed circumstances of his experiment. We do not see any contradiction between the descriptions of the instability and roll-up in this paper and those of Reynolds; in fact, there are certainly several aspects that are in common.

4. Concluding remarks

The aspects of the puff structure observed here are summarized diagrammatically in figure 16. The fact that vortex roll-ups are taking place near the wall in much the same way as in slugs (Wygnanski & Champagne 1973) or boundary-layer turbulence spots, needs some clarification. Coles (1981) has pointed out that Wygnanski & Champagne classified puffs and slugs 'strictly in terms of origin; disturbed entry for the puff, boundary layer instability for the slug'. Thus, strictly speaking, nothing has been said about the instability of the puff. Coles, on the other hand, prefers to distinguish between the puffs and slugs only by the fact that they appear at low and high Reynolds numbers respectively, the boundary being marked by the gradual disappearance of the downstream low-turbulence (or the so-called 'relaminarizing') region. According to him, a distinction in terms of origin is inappropriate. The approach of Coles is preferable also because it does not imply any basic difference in the instability process.

The description of the puff structure presented here is by no means complete, but the existence of the helical motion and the organized wake-like structures are clear.

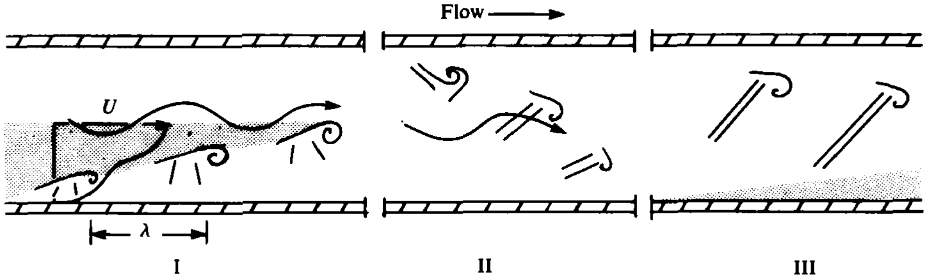

FIGURE 16. Diagrammatic representation of a puff; I: laminar plug, helical motion and dye pattern of structures formed at the trailing interface; II: fully turbulent region; III: dye pattern in the 'relaminarizing' region. In I, the structures formed at one azimuthal location only have been represented. The grey tone indicates a laminar-like field.

We believe these aspects help provide a framework for the treatment of the three-dimensional instability and the production of turbulence in terms of vortex stretching.

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