The flow structure of a puff

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From time-resolved stereoscopic particle image velocimetry measurements over the entire circular cross section of a pipe, a first-of-its-kind quasi-instantaneous three-dimensional velocity field of a turbulent puff at a low Reynolds number is reconstructed. At the trailing edge of the puff, where the laminar flow undergoes transition to turbulence, pairs of counterrotating streamwise vortices are observed that form the legs of large hairpin vortices. At the upstream end of the puff, a quasi-periodic regeneration of streamwise vortices takes place. Initially, the vortex structure resembles a travelling wave solution, but as the vortices propagate into the turbulent region of the puff, they continue to develop into strong hairpin vortices. These hairpin vortices extract so much energy from the mean flow that they cannot be sustained. This structure provides a possible explanation for the intermittent character of the puffs in pipe flow at low Reynolds numbers.

Keywords: pipe flow; transition; vorticity

1. Introduction

Since the original experiments of Reynolds (1883) on the onset of turbulence in a pipe, it has been known that near transition, i.e. for Reynolds numbers $Re \equiv U_b D/n$ (where $U_b$ is the mean bulk velocity; $D$ is the pipe diameter; and $n$ is the kinematic viscosity) between 1900 and 2800, laminar flow and turbulent regions, named ‘flashes’ or ‘puffs’, can coexist. These puffs travel through the pipe at about the bulk velocity and can persist for very long times. Referred to as ‘equilibrium puffs’, they are thought to represent the ‘minimum flow unit’ that can sustain a turbulent flow state. It therefore represents one of the most simple forms of turbulent shear flow. The turbulent region is approximately three pipe diameters long and entirely restricted to the transition region at the upstream end of the puff. This means that the transition process and the process that sustains the turbulence are in fact one and the same. It may be anticipated that a better understanding of the flow dynamics in a puff will also contribute to our understanding of the self-sustaining process of wall-bounded turbulence in general, which lies at the heart of much turbulence research.

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In this paper, we report the results of measurements with stereoscopic particle image velocimetry (SPIV) of a puff, measured at a Reynolds number of 2000. These results for the first time give a detailed description of the instantaneous spatial structure.

(a) Previous observations

Lindgren (1957, 1969) was one of the first after Reynolds to return to the problem of the onset of turbulence in a pipe. He used a streaming double refractive method to observe the flow, and he gave a detailed description of the development of puff disturbances in the flow as a function of the Reynolds number. Partly obstructing the pipe entrance, large initial flow disturbances were created. For \( Re \leq 2000 \), the perturbed flow returned to the laminar state. Only occasionally the primary disturbance initiated a turbulent spot or ‘flash’, characterized by intensive small-scale velocity fluctuations. When a flash formed, it travelled some distance down the pipe, typically not more than 100–130 \( D \), before it decayed. For \( 2000 \leq Re \leq 2400 \), some of the turbulent flashes began to travel long distances down the pipe, unaltered in length (on average) and without any sign of damping effects. For \( 2400 \leq Re \leq 2800 \), a flash may split into two, the new one ahead of the parent flash. Repeated splitting results in a streak composed of discrete flashes, intermixing and changing during their travel downstream. For \( Re \geq 2800 \), the flow remained fully turbulent downstream from the initial flow disturbance.

Wygnanski et al. (1975) made a detailed study of the equilibrium puff, which appeared to propagate down the pipe without any change in length or form for \( 2200 < Re < 2300 \). At the upstream end of the puff, there is a sharp laminar–turbulent interface, whereas at the downstream end, the interface is not so well defined. The average velocity field inside the equilibrium puff was obtained from phase-averaged hot-wire measurements. In a coordinate system moving with the puff, the average velocity field displays two half open recirculations, one on each side of the upstream edge (see Wygnanski et al. 1975, fig. 8). These mean recirculations were interpreted as an indication for the presence of axisymmetric toroidal vortices in the flow.

Breuer & Haritonidis (1991) investigated the flow in a puff with a rake of 10 hot wires arranged both radially and azimuthally. They believed that the large spikes, observed simultaneously in the velocity–time traces of all hot wires, are related to the passage of toroidal vortices. It was suggested that these toroidal vortices were created at the upstream edge of the puff, then propagate through the puff and finally break up near the downstream edge. Within one puff, typically three to four large velocity spikes were observed.

Bandyopadhyay (1986) made beautiful LIF flow visualizations of the equilibrium puff for \( Re = 2250 \), some of which are reproduced in figure 1. From the large asymmetry between the structures visualized in the upper and lower parts of the pipe, it was concluded that the toroidal vortex model proposed by Wygnanski & Champagne (1973) does not show up in the instantaneous flow fields. Apparently, the ensemble averaging leads to smearing of information on the three-dimensional structures in the flow, which have a considerable randomness in their temporal and spatial position. Shan et al. (1999) carried out a direct numerical simulation of the flow in a puff at \( Re = 2200 \), and strong counterrotating streamwise vortices were found close to the downstream edge of the puff.
Darbyshire & Mullin (1995) investigated transition in pipe flow as a result of an instantaneous injection of fluid in a constant mass flow experiment. Their results on the development of puffs and slugs are similar to that observed in pressure-driven systems. This shows that the presence of puffs at low Reynolds number in pipe flow cannot be explained by variations in the flow rate and the Reynolds number. These experiments revealed that there exists no clear border between initial conditions that trigger transition to turbulence and those that do not.

Draad et al. (1998) disturbed the flow by time-periodic blowing and suction of fluid through a narrow slit in the wall. For $2000 < Re < 2200$, the number of puffs generated by the disturbance is found to depend rather sensitively on the frequency and amplitude of the disturbance. Below a critical amplitude, puffs are never observed, but when the amplitude is increased, a growing number of puffs are generated, until at a particular amplitude a maximum is reached. Thereafter, a further increase in the disturbance amplitude leads to a reduction in the number of puffs.

In the case that the laminar-to-turbulence transition is triggered by a smooth and well-defined disturbance of the laminar pipe flow, e.g. by periodic injection and extraction of fluid from the wall, much more detailed information is available about the initial development of the disturbance and the following transition (Eliahou et al. 1998; Ma et al. 1999; Han et al. 2000; Reuter & Rempfer 2000; van Doorne 2004). At the initial stage of the transition, streamwise vortices, low-speed streaks and shear layers are formed. In the late stage, the shear layers become unstable and hairpin-like vortices develop in the flow. This transition scenario has also been observed in channel flow and boundary-layer flow, and it seems to be general for most shear flows. This is probably related to the fact that the structures observed in the transition process resemble those observed in fully developed wall turbulence. It may therefore be anticipated that similar structures will play an important role in the flow in a puff.
Recent developments

Recent findings in nonlinear dynamics have revealed exact solutions of the Navier–Stokes equations for a pipe flow at Reynolds numbers $Re>1300$, in the form of *travelling waves* (TW), that exist next to the Hagen–Poiseuille solution (Faisst & Eckhardt 2003; Wedin & Kerswell 2004). These TW solutions represent features of a self-sustaining process (Waleffe 1997; Eckhardt *et al.* 2007), and flow patterns strongly reminiscent of these TW solutions were observed experimentally in puffs by Hof *et al.* (2004).

Faisst & Eckhardt (2004) investigated the lifetime of flow disturbances reminiscent of puffs in a pipe as a function of the Reynolds number for $1600\leq Re\leq 2200$. They found that the probability for the disturbances to survive a time $T$ had an exponential distribution, characteristic of a memoryless process (such as radioactive decay). Initially, the results appeared to indicate that the mean lifetime $\tau$ (defined as the median of the probability distribution) diverges to infinity for $Re=2250$, based on a linear extrapolation of $\tau^{-1}$ to zero. Experiments by Peixinho & Mullin (2006) using flow visualization confirmed the exponential decay of puffs for $1580\leq Re\leq 1740$, but predicted a divergence at $Re=1750\pm 10$, by extrapolation of $\tau^{-1}$ following Faisst & Eckhardt (2004). These experimental findings appear to be confirmed by direct numerical simulations of Willis & Kerswell (2007), although they report a value of $Re=1870$ for which divergence would occur.

However, it was demonstrated by Hof *et al.* (2006) from measurements of lifetimes in very long pipes (with lengths up to $7500D$) that the reciprocal lifetime $\tau^{-1}$ as a function of $Re$ is *not* linear, but that it has a distinct exponential form for $Re<2200$. This does not only invalidate the linear extrapolation of $\tau^{-1}$, but also implies that turbulent puffs do not represent a sustained turbulent flow state and that turbulence should be considered as a very long-lived transient state (Lathrop 2006).

Outline

From the discussion so far, it is clear that only little information is available on the flow structure in puffs and that the previous investigations do not lead to a consistent picture. Against this background, the main objective of this paper is to provide more information on the instantaneous three-dimensional structure of the flow in a puff. Our investigation is a continuation of the work by Westerweel & Draad (1996), who considered a jet-like disturbance in the laminar pipe flow and reconstructed the flow in the mid-plane of a turbulent slug by combining a sequence of particle image velocimetry (PIV) data fields. Compared with the previous experiments, the orientation of the light sheet has changed and is now perpendicular to the pipe axis. This allows us to obtain quantitative results on the instantaneous velocity field over the entire circular cross section of the pipe. For time-resolved measurements, the three-dimensional flow field can be reconstructed by applying Taylor’s hypothesis (Taylor 1938). In §2, we give a brief presentation of the experimental facility and the experimental method, and, in §3, we present the results. Based on our observations, we give an explanation for the intermittency of pipe flow at low Reynolds numbers in §4. A summary of the main conclusions is given in §5.
2. Experimental method

For our measurements, we used a Perspex pipe with an inner diameter of 40 mm and a total length of 28 m. The working fluid is water, and owing to a well-designed contraction and thermal insulation of the pipe, the flow can be kept laminar up to \( Re = 60,000 \) (Draad 1998). All measurements were carried out at 26 m from the inlet. The turbulent puffs are created 150 diameters upstream from the measurement position by the injection of a jet with a large mass flux \( (0.5 U_b \pi D^2) \) and a short duration \( (D/U_b) \) through a 1 mm hole into the fully developed laminar pipe flow.\(^1\) There should be a minimum distance of at least 100 pipe diameters between the point of injection and the measurement position to allow for the flow disturbance to develop into an equilibrium puff and to ensure that any sensitivity to the initial condition of the disturbance has disappeared (Wygnanski & Champagne 1973; Darbyshire & Mullin 1995; Hof et al. 2006; Peixinho & Mullin 2006). This distance depends on the type and magnitude of the flow disturbance (SeedeLozar & Hof 2009). The injection amplitude and mass flux are chosen in accordance with the disturbances used by Draad et al. (1998). The strong localized high-velocity jet reduces the time for the disturbance to develop into an equilibrium puff in comparison with a small-amplitude distributed disturbance.

SPIV (Prasad 2000) was applied to measure the instantaneous three-component velocity field over the full circular cross section of the pipe. The vector spacing is 0.7 mm, and the uncertainty in the measured velocity is approximately 1 mm s\(^{-1}\) (root-mean-square (r.m.s.) value), which corresponds to 2 per cent of the bulk velocity. PIV measurements are taken at a rate of 62.5 Hz. As the light sheet is oriented perpendicular to the main flow direction, the flow structures are advected through the measurement plane by the mean flow. For time-resolved measurements, the quasi-instantaneous three-dimensional flow field can be reconstructed from the sequence of recorded vector fields by applying Taylor’s hypothesis (Taylor 1938). In the turbulent flow region of the puff, the velocity profile is more or less flat (so that there is a more or less uniform velocity across the cross section of the flow) and the application of a (constant) velocity to convert the temporal coordinate into a spatial coordinate seems appropriate (Westerweel & Draad 1996). For the advection velocity, we take the bulk velocity. Although this procedure is not correct in a very strict sense (owing to the shear in the mean flow, in particular in the near-wall region), it at least provides us with a good qualitative impression of the three-dimensional flow structure. The various details regarding the SPIV technique, such as the calibration procedure, the PIV vector evaluation and the measurement accuracy, are described by van Doorne & Westerweel (2007).

The development of a puff (i.e. its growth, decay, splitting, propagation velocity, etc.) is very sensitive to the exact value of the Reynolds number, which is set to \( Re = 2000 \) for this experiment. It is therefore important that the flow rate remains constant during the experiment. This is verified by the result shown in figure 2, which shows the bulk velocity \( U_b \) calculated from the streamwise velocity measured by the SPIV system over the cross section of the pipe. The time-averaged bulk velocity is 47.3 mm s\(^{-1}\) and the r.m.s. variation is 0.18 per cent.

\(^1\) This corresponds to the injection of 25 ml of water in a pipe flow with a flow rate of 3.81 l min\(^{-1}\).

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of the mean bulk velocity. A slight trend in the graph shows that there has been a change in the flow rate of the order of 0.4 per cent, which is due to pump fluctuations.

3. Results

In this section, we present the detailed results of our SPIV measurements. We present the detailed results of a single puff at a Reynolds number of 2000, which is representative of a set of 20 puffs measured at various Reynolds numbers (of which five were measured at $Re=2000$). The data are represented in a Cartesian coordinate system that is conventional for the SPIV data, i.e. the $x$-axis coincides with the plane determined by the optical axes of the cameras, the $y$-axis is normal to this plane (i.e. the common coordinate of the image planes of the cameras) and the $z$-axis is normal to the light-sheet plane.

(a) Time series

The axial velocity at the centreline of the pipe as a function of time during the passage of a puff is plotted in figure 3. Upstream from the puff (for $t>7$ s), the flow is laminar and the velocity profile is parabolic. The uncorrelated small velocity fluctuations for $t>7$ s are due to the PIV measurement noise, which is of the order of $1 \text{ mm s}^{-1}$.

At $t=5.3$ s (position $Z_2$), the velocity drops very suddenly. This position is defined as the trailing edge of the puff and defines the origin $t_0$ of the non-dimensional downstream distance

$$z^* = (t_0 - t) U_b.$$  \hspace{1cm} (3.1)
Somewhat further downstream at position $Z_3$, a second spike is observed, and the next sharp decrease in the velocity at $Z_4$ is followed by a series of smaller fluctuations (at $Z_5$, ..., $Z_7$). Similar observations of the centreline velocity were made by Wygnanski & Champagne (1973) and Darbyshire & Mullin (1995). In experiments on transition in pipe flow, Han et al. (2000) showed that similar spikes were related to (a series of) hairpin-like vortices in the flow.

Around $Z_7$, the flow becomes laminar again. Immediately downstream from the relaminarization, the velocity profile is still relatively uniform, and the centreline velocity is relatively low. Further downstream, the parabolic velocity profile is restored by the gradual growth of the viscous shear layers from the wall, hence the slow increase in the centreline velocity in the downstream direction that continues for $z^* > 6$ towards $u_z \sim 2U_b$. Further note that the rapid velocity fluctuations around $Z_2$ are represented by approximately 10 measurement points, which confirm that the SPIV measurements are indeed time-resolved. The cross-sectional average of the kinetic energy of the in-plane velocity ($E_{xy} = \langle u_x^2 + u_y^2 \rangle$) and of the axial velocity ($E_z = \langle u_z^2 \rangle$) is presented in figures 4 and 5. The wavy pattern in $E_z$ and the sequence of distinct peaks in $E_{xy}$ seem to indicate a quasi-periodic organization of the flow in a puff. A peak in $E_{xy}$ roughly coincides with a minimum in $E_z$ and a sharp decrease (in the downstream direction) in the axial velocity (figure 3). This shows that the turbulent energy of the in-plane velocity ($E_{xy}$) is extracted locally from the energy of the mean flow ($E_z$). The strong in-plane motions related to the maximum in $E_{xy}$ advect slow moving fluid from the wall to the centre of the pipe, and thus induce the sharp decrease in the centreline velocity.

(b) Planar data

The sequence of vector fields displayed in figure 6 gives a more direct view of the flow structure. Streamwise vortices, streaks and shear regions have been visualized by the axial vorticity, the axial velocity and the ‘in-plane vorticity’,
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$$\omega_{xy} = \sqrt{\left(\frac{\partial u_z}{\partial x}\right)^2 + \left(\frac{\partial u_z}{\partial y}\right)^2}$$

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Figure 4. Kinetic energy of the in-plane velocity ($E_{xy}$).

Figure 5. Kinetic energy of the in-plane ($E_{xy}$) and axial ($E_z$) velocity. A constant of 1.15 has been subtracted from $E_z$ in order to plot the two lines on a single scale. Grey line, $\langle u_x^2 \rangle / U_b^2 - 1.15$; black line, $\langle u_x^2 + u_y^2 \rangle / U_b^2$. 

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Figure 6. (a–c) Results of the PIV measurements in a puff: (i) axial vorticity, (ii) axial velocity and (iii) in-plane vorticity. The numbers are explained in the text. In (a), the arrow (top left) represents the location and direction of the original flow disturbance.

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where $x$ and $y$ are the in-plane coordinates, and $u_z$ is the out-of-plane (i.e. axial) velocity component. For details regarding the computation of these quantities, we refer to van Doorne (2004).
The first flow field ($z^* = -3.4$) is measured upstream from the puff, where the laminar flow has a nearly parabolic velocity profile. A first weak disturbance is observed, which consists of a low-speed streak at the wall (1) and a region of increased shearing (2) at the top of the streak.

Further downstream at $z^* = -1.1$, a number of low-speed streaks and related shear regions have formed periodically around the circumference of the pipe. At this position, the disturbance of the laminar flow is restricted to the wall region, and the central part of the flow remains unaffected. The graph of the axial vorticity reveals the presence of several streamwise vortices as indicated by (3) and (4). Quite remarkable is that the strongest wall-normal velocity fluctuations are directed towards the wall (5 and 6), and thus form regions with a high velocity close to the wall. Only a small distance downstream, at $Z_1$ (for $z^* = -0.82$), $E_z$ reaches a first local minimum (figure 5).

Figure 6. (Continued.)
Around \(z^* = -0.53\), \(E_{xy}\) reaches a local maximum (figure 4), which is related to the combined action of several strong vortices that have a symmetric configuration with respect to the indicated line (7). The development of the disturbance is stronger in the left half of the pipe, but also in the right half of the pipe, the streaks have become more pronounced, and the shear layers have moved somewhat further towards the centre of the pipe. The centreline velocity is still not much affected at this point, as follows from figure 3.

The vector field at the trailing edge of the puff (\(Z_2\) at \(z^* = 0\)) shows a strong ejection of low-speed fluid into the central region of the pipe (10), which explains the sudden decrease in the centreline velocity (‘spike’) in figure 3. This event is clearly related to the large hairpin-like vortical structure (9). The two counterrotating vortices that form the legs of the hairpin are strongly inclined with respect to the wall, which results in the rather elongated isocontours of the streamwise vorticity. The tip of the hairpin vortex (11) that connects the two legs is characterized by a large value of the in-plane vorticity. A second pair of strong counterrotating vortices (8) is seen to lift a considerable amount of fluid away from the wall, which might have deflected the direction of the hairpin vortex (9). Upstream from the trailing edge at \(\Delta z = 0.15\), the vector fields show strong motions parallel to the wall, and the isocontours of the streamwise vorticity form rather elongated regions close to the wall. One vortex leg is considerably stronger than the other, and this pulls the entire structure to one side at the upstream end of the hairpin vortex.

The second large spike in the centreline velocity (\(Z_3\) at \(z^* = 0.74\)) almost coincides with the enormous peak in \(E_{xy}\) and the large minimum in \(E_z\). This extreme event is related to a very strong hairpin vortex in the flow. This is most easily recognized in the vector field for \(z^* = 0.83\) (figure 6), which shows a very large low-speed region (16) in combination with the legs (14) and tip (17) of the hairpin vortex. The maximum in \(E_{xy}\) occurs slightly further upstream at \(z^* = 0.74\) (\(\Delta z = 0.1D = 4\) mm). The very large cross flow (13) observed at this position extends over the entire cross section of the pipe and is directed away from the hairpin vortex. This suggests that the relatively fast fluid at this point is deflected by the low momentum region of the hairpin vortex slightly ahead. Furthermore, note the striking symmetry of the streamwise vorticity distribution with respect to the indicated line (12).

After the energetic event at \(Z_3\) (\(z^* = 0.74\)), there follows a rapid decay of the turbulent energy \(E_{xy}\) in the downstream direction (figure 4), and the flow returns to the laminar state. Two rather marked local maxima in \(E_{xy}\) can still be observed at \(Z_3\) and \(Z_5\), and the first is also accompanied by a strong decrease in the centreline velocity and in \(E_z\). In view of our previous description of the results, these two events may correspond to two decaying hairpin vortices. At \(Z_4\) (figure 6), however, there are no clear indications for the legs, the tip and the low-speed region related to a hairpin vortex. At \(Z_5\), the vorticity distribution (18) and the region of low axial velocity give some more support for the idea that part of the decaying turbulent structures still resembles a typical hairpin vortex.

The last disturbances, visualized for \(Z_6\), are some weak streamwise vortices in the central region of the pipe. At \(z^* = 6.3\), the flow is completely relaminarized, but the axial velocity profile is still not axisymmetric, and the centreline velocity is much lower than for the parabolic velocity profile. Further downstream, the parabolic velocity profile will be restored by the gradual growth of the viscous boundary layers from the wall.
The flow structures described above are representative of the structures observed in all measured puffs, and they show a strong resemblance to the structures that were observed in flow visualizations of puffs at $Re=2100$ and $2200$ that pass through a planar cross section of the pipe illuminated by a light sheet (van Doorne 2004).

\[\text{(c) Volumetric data}\]

In the discussion of the various cross sections obtained from the SPIV measurements, we have concentrated on the overall organization of the flow, and it appeared that large hairpin-like vortices form an important flow structure. However, the flow contains many other (small-scale) motions that were not explicitly mentioned. These structures largely determine the chaotic appearance of the flow, and this is nicely illustrated by the three-dimensional view of the isocontours of the streamwise vorticity in figure 7 (see also similar results presented in deLozar & Hof 2009). In this complicated structure of streamwise vortices, it is difficult to distinguish the pairs of counterrotating vortices that together form a hairpin-like structure. It seems that a substantial part of the vortices does not occur in pairs at all, but exist rather individually, which is in agreement with the observations made by Robinson (1991) based on numerical simulations of a turbulent boundary layer.

In figure 7b, only the vortices in the lower half of the pipe ($y<0$) are shown. Some of the vortices, indicated by the letters (a)–(d), follow each other quasi-periodically in the downstream direction. This is quite similar to the periodic...
organization of the streamwise vortices found in the exact TW solutions (Faisst & Eckhardt 2003; Wedin & Kerswell 2004; Hof et al. 2005). In a previous analysis of this very same measurement of a turbulent puff, it was already shown that for certain radial cross sections, the flow displayed a striking similarity to these TW (Hof et al. 2004). Further note that the downstream end of the vortices (a–d) in the puff coincides approximately with the sequence of spikes observed in the streamwise velocity and in $E_{xy}$ (at $Z_l-Z_r$). These spikes were found to be related to the occurrence of strong hairpin-like vortices, rather different from the travelling wave solutions. The travelling wave solutions, however, are known to be unstable, and we anticipate that this may result in the development of a hairpin vortex at the downstream end of the streamwise vortices, as is observed in our measurements.

This brings us to the following picture of the vortex structure and flow dynamics. At the upstream end of the puff, a quasi-periodic regeneration of streamwise vortices takes place. Initially, the vortex structure resembles the travelling wave solution, which is represented as a saddle-node in state space. Given that these solutions are highly unstable, the flow represented in state space moves away from the TW solution along the most unstable direction. Given our observation of TW-like flow states and the presence of hairpin-like structures, we conjecture that the vortices in the TW-like flow state continue to develop into strong hairpin vortices. These hairpin vortices extract so much energy from the mean flow that they cannot be sustained for long, which results in the intermittent character of the pipe flow at low Reynolds numbers, as will be explained in §4. The amount of energy that is extracted from the mean flow can be quantified from figure 5, where the mean axial kinetic energy (averaged over the pipe’s cross section) decreases by $0.1 U_b^2$. There is a fair correlation between the decrease in the axial kinetic energy and the peaks in the in-plane kinetic energy, which suggests that extraction of the axial kinetic energy from the laminar flow into turbulent fluctuations is related to the observed hairpin vortices. The deficit between the variation in the axial kinetic energy and the in-plane kinetic energy implies that the axial kinetic energy is converted into pressure fluctuations or is directly dissipated by viscous effects.

### 4. Discussion

A long-standing question is why pipe flow becomes only intermittently turbulent at low Reynolds numbers, and why does it not evolve into fully developed turbulence? From experiments, it is known that a highly disturbed (turbulent) flow does not sustain the velocity fluctuations for long, but after a partial relaminarization of the flow, the turbulent puffs appear to be non-fading (Lindgren 1957; Wygnanski & Champagne 1973). Apparently, the laminar flow in between the turbulent regions is crucial to sustain the turbulent motions within the puffs that can travel down the pipe without any damping effects until they suddenly decay.

When the shear layer at the wall of the pipe is sufficiently thick, transition to turbulence can take place, which is observed for the (nearly) parabolic velocity profile at the upstream end of a puff. If we follow the fluid in a Lagrangian frame of reference on its way through the puff (the downstream velocity of puffs is somewhat
smaller than the bulk velocity), the turbulent motions redistribute the axial velocity, which results in a relatively uniform flow in the centre of the pipe and a rather thin shear layer at the wall. Because such a thin shear layer is stable, it cannot maintain the turbulent motions that are indeed found to decay at the downstream end of the puff. After the flow has relaminarized, the velocity profile will start to develop again until the parabolic velocity profile has been re-established and transition can be triggered by the next (downstream) turbulent puff.

An alternative explanation follows from a balance of the mechanical energy over (the transition interface of) the puff. In a frame of reference moving with the puff (approx. 0.95 $U_b$), the kinetic energy flux related to the laminar inflow at the upstream end of the puff is larger than the loss of the kinetic energy at the downstream end of the puff, where the velocity profile is relatively uniform in the centre of the flow (figure 8). The fluid that enters the turbulent region with a high velocity at the upstream end of the puff thus provides the necessary energy to sustain the turbulent motions inside the puff. This energy is quickly converted into turbulent motions and dissipated, which results in an almost uniform velocity profile at the downstream end of the puff. The hairpin vortices that pass this (moving) plane decay quickly, because it is no longer possible to extract energy from a uniform flow; the flow then relaminarizes, and further downstream, the wall shear layers develop and the centreline velocity again increases. When the kinetic energy has reached a sufficiently high level, another turbulent puff can be sustained. As each hairpin structure generates new hairpin structures, the turbulent flow state is maintained. When a hairpin fails to generate a new hairpin, the puff rapidly decays within several integral time scales, which explains the rather sudden decay of puffs that has been observed in experiments (Peixinho & Mullin 2006; Hof et al. 2006).

**Figure 8.** Normalized kinetic energy flux $\Phi_E = \int_0^R (1/2)(U_z - U_t)^32\pi r \, dr/(1/2)U_0^3\pi R^2$ through a moving cross section in the pipe, as a function of the downstream velocity ($U_t/U_b$) of this cross section. The laminar velocity profile (solid line) is parabolic and the turbulent profile (dashed line) is approximated by a 1/7 power law (Hinze 1975). The dotted line represents the difference.

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From this understanding of the global flow dynamics, several other observations reported in the literature can be understood. Both Reynolds (1883) and Lindgren (1957) report that the turbulent puffs appear at least 20–30D from the disturbed entrance of the pipe. This is related to the distance needed for the shear layers to develop to the point that transition to turbulence can take place.

Rubin et al. (1980) generated two subsequent puffs with a variable distance between them. When the distance was reduced, the downstream puff appeared to be smaller. Further reduction in the distance resulted in the occasional, and later complete, disappearance of the downstream puff. The explanation is that the upstream puff extracts its energy from the undisturbed laminar flow coming from further upstream, and therefore it is not affected by the preceding puff further downstream. Immediately downstream from the upstream puff, the relaminarized flow has a much smaller kinetic energy flux, which then increases further downstream. When the distance between the two puffs is not so large, the downstream puff receives thus less kinetic energy from the laminar inflow and is therefore smaller. When the distance becomes too small, the kinetic energy flux will become too small to sustain the velocity fluctuations of the downstream puff, which will then decay. At low Reynolds number, there is thus a minimal distance between two subsequent puffs. Lindgren (1957) further mentioned that as the Reynolds number increases, the turbulent puffs elongate and follow each other more closely.

Closely related to the previous point is the observation by Wygnanski et al. (1975) that after splitting of a puff into two parts, the upstream puff will grow more rapidly than the downstream puff. Wygnanski & Champagne (1973) did not observe puffs for $Re<2000$, while Darbyshire & Mullin (1995) and Peixinho & Mullin (2006) were still able to trigger puffs at $Re=1800$ and below. This may be explained by the different disturbances that were used. Darbyshire & Mullin (1995) and Peixinho & Mullin (2006) created a localized disturbance by the injection of some fluid into a fully developed laminar flow. There is thus a maximal inflow of the kinetic energy at the upstream end of the disturbance, which can sustain the turbulent motions at very small Reynolds numbers. Wygnanski & Champagne (1973), on the other hand, applied a continuous and large disturbance at the entrance of the pipe. Especially at low Reynolds numbers ($Re<2000$), the velocity profile must be nearly parabolic to sustain a turbulent puff. By the time the velocity profile has reached this point, all initial disturbances have been dissipated and therefore no puffs will appear.

5. Conclusion

We investigated the flow structure in a puff with the help of time-resolved SPIV measurements with the laser light sheet placed perpendicular to the main flow direction. We thus obtained quantitative experimental data that were previously not available. The measurements provide data for all three components of the velocity over the entire circular cross section of the pipe, and these are converted into a quasi-instantaneous three-dimensional flow field of the puff. The three-dimensional plots of the isocontours of the streamwise vorticity, as shown in figure 7, give a good impression of the complicated structure of the flow inside the
puff. It was found that the large fluctuations of the centreline velocity (spikes) close to the trailing edge of the puff are related to the large hairpin vortices in the flow. It was further found that the spikes in the centreline velocity coincide with large spikes in the kinetic energy of the in-plane velocity ($E_{xy}$) and a sharp decrease in the energy of the axial velocity ($E_z$). This shows that the hairpin vortices extract energy from the mean flow to produce non-streamwise velocity fluctuations, which result in the turbulent motions. The spikes have a spatial extent in the axial direction of 0.095$D$ (full width at half maximum), which means that a high spatial resolution in the axial direction is required to observe these structures. (There is no report of these spikes in the simulations of puffs by Willis & Kerswell (2007), which have an axial resolution of 0.13$D$.)

From these measurements, it follows that at the upstream end of the puff, the fluid is lifted slowly from the wall by pairs of weak counterrotating streamwise vortices that appear at approximately three to six locations around the circumference of the pipe. One pair of streamwise vortices develops into a sequence of approximately three streamwise-aligned hairpin vortices that are much larger than all other vortices. The hairpin vortices grow in the downstream direction, and at the trailing edge of the puff, a single hairpin vortex occupies almost the entire cross section of the pipe. Downstream from the trailing edge, the fluid is first vigorously mixed by many small-scale structures, after which the flow quickly relaminarizes and leaves the puff. These observations are consistent with the visualizations by Bandyopadhyay (1986), and they suggest that the continuous transition at the upstream end of the puff is the result of a quasi-periodic regeneration of hairpin-like vortices.

In view of the current observations, which reveal a large asymmetry of the flow around the pipe axis and the important role of streamwise vortices, it has to be concluded that the toroidal (axisymmetric) vortex model, proposed by Wygnanski & Champagne (1973) based on the data of the ensemble-averaged flow field, is inappropriate to describe the flow dynamics. Instead, a quasi-periodic regeneration of streamwise vortices takes place at the upstream end of the puff. Initially, the vortex structure resembles the TW solutions, but owing to the instability of the TW, vortices continue to develop into strong hairpin vortices. There is clearly a large similarity between the quasi-periodic regeneration of hairpin vortices in a puff and the dynamics of hairpin packets observed in the near-wall region of turbulent flow at much larger Reynolds numbers, which is, for instance, described by the vortex model of Smith (1984) and Smith et al. (1991) and that was observed by Adrian et al. (2000; see also Adrian 2007). Moreover, when the Reynolds number is slowly increased, the hairpin vortices in the puff will gradually decrease in size and the flow will continuously change into fully developed turbulence. This suggests that the high intermittency observed near the wall region in fully developed turbulent shear flow (den Toonder & Nieuwstadt 1997) may be governed by mechanisms similar to those that govern the intermittency of puffs at very low Reynolds numbers, and for which we have given two explanations based on the boundary-layer thickness and a balance of the mechanical energy.

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