RAPID COMMUNICATIONS

PHYSICAL REVIEW E VOLUME 47, NUMBER 1 JANUARY 1993

From small scales to large scales in three-dimensional turbulence: The effect of diluted polymers

D. Bonn
Laboratory for Physical Chemistry, University of Amsterdam, Nieuwe Achtergracht 127, 1018 WS, Amsterdam, the Netherlands

Y. Couder
Laboratoire de Physique Statistique de l'Ecole Normale Supérieure, 24 rue Llomond, 75231 Paris CEDEX 05, France

P. H. J. van Dam
Laboratory for Physical Chemistry, University of Amsterdam, Nieuwe Achtergracht 127, 1018 WS, Amsterdam, the Netherlands

S. Douady
Laboratoire de Physique Statistique de l'Ecole Normale Supérieure, 24 rue Llomond, 75231 Paris CEDEX 05, France and Laboratoire de Physique de l'Ecole Normale Supérieure de Lyon, 46 Allée d'Italie, 96364 Lyon CEDEX 07, France

(Received 14 May 1992)

In a turbulent flow, diluted polymers are shown to inhibit the formation of coherent high-vorticity filaments and to reduce correspondingly the rate of formation of large eddies. This effect demonstrates that in a three-dimensional turbulent flow, some nondissipative small-scale structures, the vorticity filaments, are nuclei of formation of large-scale structures. The reduction of the energy dissipation rate also suggests that this breakdown of the vorticity filaments into eddies is important for the formation of the dissipative structures.

PACS number(s): 47.25.−c, 61.25.Hq, 47.55.Bx, 47.80.+v

Flexible polymers have been known for a long time to reduce turbulent drag [1], a very striking phenomenon in view of the high dilutions at which it occurs. Most attempts to understand turbulent-drag reduction are based on the fact that the polymer molecules, coiled in a spherical shape at rest, can be uncoiled and stretched under a stress that the fluid exerts on them [2–4]. For large-scale hydrodynamic motions, the polymer molecules are advected passively and there is no reason why they should affect the flow. At small scales, however, the stresses can become comparable to the elastic modulus of the polymer so that it can undergo a coil-stretch transition; different models have thus proposed that either in the boundary layers [2] or in the dissipative range [3,4] the stretching of the molecules either modified the viscosity [2,4] or introduced a viscoelastic behavior in the fluid [3].

Independent of the type of activity of the polymer (viscous or elastic), the main difficulty in interpreting the drag reduction could well have been due to the implicitly assumed structure of turbulence. The Kolmogorov cascade [5] implies that in the steady regime of turbulence, energy is fed into the flow at large scales and dissipated at small scales. The original Kolmogorov theory is statistical and does not address the problem of the spatiotemporal structure of the turbulent flow. It is often thought, however, that the Kolmogorov spectrum corresponds to a hierarchy of vortices of all sizes, each vortex of a given size being responsible for the formation of the vortices of a smaller size, the smallest structures being *exclusively dissipative* [6]. Within this model it is difficult to see how a change in these smallest scales could lead to a global effect very different from that of a change of the viscosity. Recently there have been several indications suggesting that the structure of the turbulent flows is in fact more complex. The time series of the velocity [7] or of the vorticity [8] in one point have strong intermittent bursts usually ascribed to the effect of energetic coherent structures. Measurement of spatial velocity gradients [9] shows that their probability distribution function is non-Gaussian, a possible signature of this intermittency. Several numerical simulations [10–14] have shown the existence of high-vorticity regions structured in tubes while the dissipative regions were layer shaped [14]. Finally in a recent experiment (Douady and co-workers [15]) the zones of minimum pressure in a turbulent flow were singled out. These are regions where there is simultaneously strong vorticity and weak dissipation [16]. They were observed directly using a liquid seeded with bubbles. This technique confirmed the filamentary structure of these regions and also permitted one to reach the dynamics of their formation and destruction. The filaments appear abruptly by the rolling-up of thin layers where both shearing and stretching coexist; they have a diameter of the order of the dissipation length scale, but can have different lengths, up to the injection length scale. They are unstable and undergo vortex breakdown [17] by formation of helical distortions. The longest filaments are then observed to be transformed into large, long-lived eddies. This was the first direct observation in a three-dimensional (3D) turbulent flow of strong, coherent small-scale structures forming the nuclei of development of large-scale structures. This dynamics suggests that, by acting only on the small scales of a turbulent flow, not only its dissipation but also its whole structure could be modified. It is the possibility that this is the main role of diluted polymers that we wish to explore.

We therefore undertook an investigation of the influence of the polymers on the dissipation rate and on the flow structures in the same experimental system in which the filaments had been observed. The experimental cell [15] is a vertical cylindrical container with a rotating disk of radius $r_0 = 5$ cm at each end. These two disks have high rims [15], are 15 cm apart from each other, and can be rotated independently at angular frequencies f_0 up to 20 Hz. When they rotate with opposite velocities, the fluid is forced into two rotations separated by a strong shear. In this way, a strongly turbulent flow is obtained in the central region of the cell with an estimated integral Reynolds number of the order of $R_I \approx \pi f_0 r_0^2/\nu$, where ν is the kinematic viscosity of water. For $f_0 = 15$ Hz, we thus have $R_I \approx 120\,000$.

In our experiment, the reduction of the energy dissipation rate is the equivalent of drag reduction. This is measured by the input power P in the electrical motors necessary to obtain a given rotation velocity of the disks (after subtracting the power necessary to rotate them at the same velocity in an empty cell). For pure water, the input power per unit mass is proportional to f_0^3, a scaling relation expected in a turbulent flow. Measurements were performed with two different polymers (polyethylene oxide) of molecular mass $M_1 \approx 3\times10^6$ amu (Polyox WSR301) and $M_2 \approx 5\times10^6$ amu (Polyox coagulant). The small polymer gives a steady drag reduction of the order of $(10\pm1)\%$ for a concentration of 50 parts per million by weight (wppm). With the longer polymer a larger drag reduction (up to 25% for 20 wppm) is obtained immediately after the injection, but this effect vanishes slowly with time [Fig. 1(a)]. At different times after the injection of polymer, samples of the turbulent liquid were taken with a syringe. Using photon-correlation spectroscopy [18], we obtained a measure of the size of the coiled molecules at rest [19]. Figure 1(b) shows that the average radius R_2 of the large molecules M_2 diminishes with the time during which they have been exposed to the turbulence (at $f_0 = 18$ Hz). At this frequency the smaller polymer M_1 remains unaffected. This mechanical degradation of the polymer proves that in the turbulent flow the stresses have been strong enough not only to stretch the longer molecules but also to tear them apart. The degradation is slow, suggesting it is only in very limited zones of the flow that the stress is large.

In order to observe the effect of the polymers on the flow structures we use the visualization technique described in Ref. [15], seeding the fluid with small bubbles. The basic process of this technique is the migration of these bubbles towards the low-pressure regions in which vorticity is large and dissipation small [16]. The median region of the flow is observed with two synchronized videotape recorders, each providing 50 images per second. On the first one, using a long exposure time (1/50 s) the motion of the bubbles reveals the large-scale velocity field. The second, with a short exposure time (1/2000 s), only showed the concentration of the bubbles which is directly related to the extrema of the pressure field. The experimental procedure is to start the experiment with pure water, record the turbulence, and then add the polymer by injecting it with a needle in the central region of the cell.

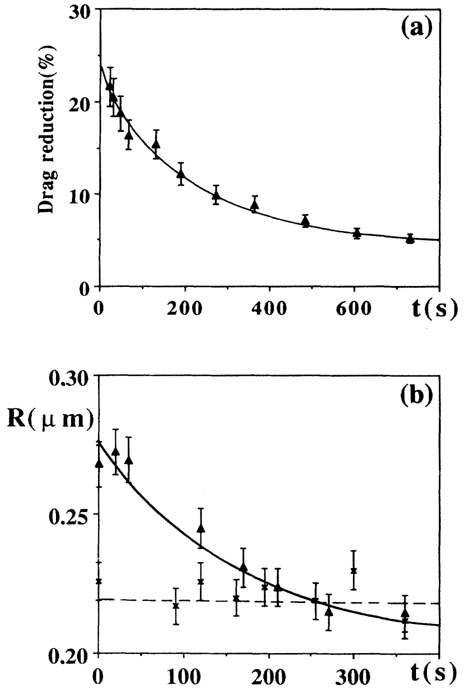

FIG. 1. (a) Drag reduction as a function of time. The polyox solution ($M_2 \approx 5\times10^6$ amu) is injected at $t = 0$, the resulting concentration is 20 parts per million, and the rotation frequency is 17.8 Hz. (b) Measurement of a mean radius of the polymer as a function of the time during which they were exposed to a turbulent flow at $f_0 = 17.8$ Hz. Crosses, initial $M_1 \approx 3\times10^6$ amu; triangles, initial $M_2 \approx 5\times10^6$ amu.

In pure water, once a steady regime of the flow is set, a very turbulent motion of randomly scattered microbubbles is observed. As described previously, the intermittent and abrupt formation of filaments of bubbles corresponding to the regions of high vorticity is observed. The longest filaments, created directly from the basic flow, are easiest to observe. Figure 2(a) shows the aspect of one of them as seen from the side: a line of a length of a few centimeters and a width of the order of 0.1 mm corresponding to the energy injection scale L_I and the Kolmogorov dissipation scale L_K, respectively. These filamentary concentrations of high vorticity only exist during one turnover time $\tau_I = \pi L_I/U_I = 2\pi/\Omega_0 \approx 0.1$ s. The time evolution of the longest filaments can be observed: they usually undergo vortex breakdown and a large eddy is formed with a lifetime of the order of ten turnover times.

With the addition of a polymer the aspect of the flow is modified. A striking effect is a suppression of the filaments. Playing the recorded tapes in slow motion, we counted the number of large filaments formed per unit time in a given volume. Figure 3(a) shows the decrease of this number with increasing polymer concentration ($M_1 \approx 3\times10^6$ amu) for three different velocities. The reduction of the number of filaments could be simply due to the reduction of the input power, i.e., to a general reduction of the level of turbulence by, say, a change of the entrainment of the fluid by the boundary layers. This is not the case: our results show that *for the same input*

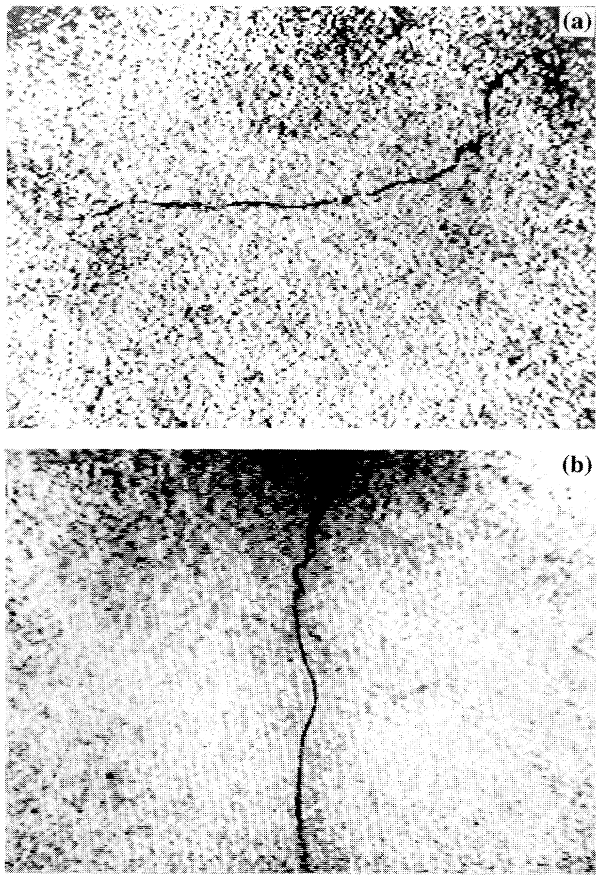

FIG. 2. Two images of high concentrations of vorticity obtained in pure water and observed with small bubbles. The tank is lit with diffuse light from behind: the bubbles appear dark on a light background. (a) A vorticity filament in a turbulent flow (exposure time 0.001 s). (b) The core of an axial vortex below a rotating disk. No photograph after the introduction of polymers is worth showing: not much is left to be seen.

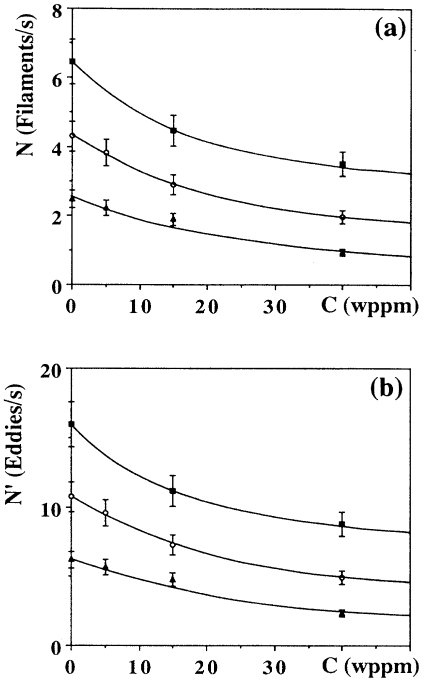

FIG. 3. (a) Statistics of the number of filaments observed in a given region of the flow per unit time as a function of the concentration (in parts per million by weight) of polymer (polyox $M_1 \approx 3 \times 10^6$ amu) for $f_0 = 8$ Hz (triangles), $f_0 = 11$ Hz (circles), and $f_0 = 15$ Hz (squares). (b) Statistics of the corresponding number of large eddies.

power the density of filaments is much smaller in a polymer solution than in pure water. With the larger polymer ($M_2 \approx 5 \times 10^6$ amu) the effect is at first even more spectacular: transitorily almost all the filaments are suppressed. However, with time they reappear: after about ten minutes, the flow regains an aspect very similar to what it was before the injection. A systematic counting is more difficult because of this time dependence. The time scale of the decrease of the polymer's activity is the same for filament inhibition and drag reduction and corresponds to that of the molecular degradation.

An important observation from the structural point of view is that the inhibition of the formation of high vorticity filaments also results in changes of the large structures of the flow. To measure this effect we counted (on the slow camera recordings) the number of the large eddies observed during a time T in a given region. Figure 3(b) shows the results of these measurements as a function of C the polymer concentration. Comparison of Fig. 3(b) with Fig. 3(a) shows that the number of eddies is reduced by the introduction of the polymer in the same proportion as the number of filaments. The total number of eddies observed is, of course, larger than the total number of filaments because their lifetime is larger by a factor of 10. In pure water the formation of the eddies had been related to the breakdown of the filaments [15]. Here we observe that, as the formation of the filaments is partly suppressed by the presence of polymers, so is the formation of the large eddies.

The suppression of the filaments suggests that the presence of the polymer inhibits the process of vorticity concentration. Such a concentration can also be obtained in a nonturbulent flow, for instance in the axial vortex of a draining rotating tank. In this case, the addition of a polymer is known to suppress the formation of the vortex core. This effect was first observed by Gordon and Balakrishnan [20] who called it vortex inhibition. Though they clearly stated that the optimal conditions for vortex inhibition were the same as for drag reduction, the two effects were not shown to be directly related to each other. In our experimental cell a steady axial vortex with a filamentary core can also be formed when only one disk is rotated [Fig. 2(b)]. With the introduction of a polymer the central concentration of high vorticity vanishes. This results probably from an elastic action of the polymer near the vortex core: by a local injection of a colored polymer it is easy to observe that this effect occurs in the bulk of the fluid before the polymer has reached any boundary.

Our results have implications both for the dynamical structure of a turbulent flow and for the action of the polymers. As for the former they confirm that not all the small scales of a turbulent flow are dissipative: there also exist transient energetic coherent small-scale structures. These are filamentary regions of *high vorticity and weak dissipation* which appear wherever a large structure (the basic flow or the large eddies) has created a thin layer with both shearing and stretching. These filaments are observed to undergo vortex breakdown. This process, though unsteady here, appears to have some of the characteristics of the breakdown widely investigated in steady conditions [17]. During this breakdown, there is simultaneously formation of a large eddy and of many small-scale structures imbedded inside it. The bubbles are violently dispersed showing a jump in pressure due to the dissipative character of the newly formed small-scale structures [16]. As for the activity of the polymers, it must be remembered that the filaments are very thin and scattered structures which occupy a very small fraction of the total volume. Therefore even if some dissipation can occur near their core it is unlikely to be responsible for an appreciable fraction of the turbulent dissipation [21]. For this reason the suppression of the filaments cannot be directly responsible for the drag reduction. But in our scheme, dissipative structures are formed as a result of the chain of processes which starts with the formation of the filaments. Therefore the present experiment suggests that the main reason [22] for which a turbulent flow is so deeply affected in its structure and in its dissipation rate by the introduction of a polymer is that in the chain of processes leading to the creation of the dissipative structures, one of them, the formation of filaments, is partly inhibited by the polymer.

---

[1] B. A. Toms, *Proceedings of the First International Rheological Congress* (North-Holland, Amsterdam, 1948).

[2] J. L. Lumley, Phys. Fluids **20**, S64 (1977).

[3] P. G. de Gennes, Physica **140A**, 9-25 (1986).

[4] J. K. Bhattacharjee and D. Thirumalai, Phys. Rev. Lett. **67**, 196, (1991).

[5] A. N. Kolmogorov, Dokl. Akad. Nauk SSSR **30**, 301 (1941).

[6] L. F. Richardson, *Weather Prediction by Numerical Process* (Cambridge University Press, Cambridge, England, 1922), p. 66.

[7] E. J. Hopfinger, F. K. Browand, and Y. Gagne, J. Fluid Mech. **125**, 505 (1982).

[8] A. Tsinober, E. Kit, and T. Dracos, J. Fluid Mech. **242**, 169 (1992).

[9] C. W. Van Atta and W. Y. Chen, J. Fluid Mech. **44**, 145 (1970).

[10] E. D. Siggia, J. Fluid Mech. **107**, 375 (1981).

[11] M. E. Brachet, D. I. Meiron, S. A. Orszag, B. G. Nickel, R. H. Morf, and U. Frisch, J. Fluid Mech. **130**, 411 (1983).

[12] Z. S. She, E. Jackson, and S. A. Orszag, Nature **344**, 226 (1990).

[13] A. Vincent and M. Meneguzzi, J. Fluid Mech. **225**, 1 (1991).

[14] M. E. Brachet, C. R. Acad. Sci. Paris **311**, 775 (1990); Fluid Dyn. Res. **8**, 1 (1991).

[15] S. Douady, Y. Couder, and M. E. Brachet, Phys. Rev. Lett. **67**, 983 (1991) and S. Douady and Y. Couder, in *Turbulence in Spatially Extended Systems,* 1992 Les Houches Proceedings, edited by R. Benzi (Kluwer, Dordrecht, in press).

[16] In an incompressible fluid [15] of density ρ, taking the divergence of the Navier-Stokes equation, we find $2\Delta p/\rho+\sigma^2-\omega^2=0$, where p is the pressure, $\omega^2=\frac{1}{2}\sum_{ij}(\partial_i v_j-\partial_j v_i)^2$ the square of the vorticity, and $\sigma^2=\frac{1}{2}\sum_{ij}(\partial_i v_j+\partial_j v_i)^2$ is proportional to the energy dissipation ($\sigma^2=\varepsilon/\rho\nu$). The pressure thus results from the repartition of ω^2 and σ^2 exactly as in electrostatics; the potential results from the repartition of negative and positive charges, respectively. The regions of minimum pressure are thus regions where there is *simultaneously strong vorticity and weak dissipation.*

[17] S. Leibovich, Annu. Rev. Fluid Mech. **10**, 221 (1978).

[18] D. W. Schaefer and C. C. Han, in *Dynamic Light Scattering,* edited by R. Pecora (Plenum, New York, 1985).

[19] The quantity obtained by photon-correlation spectroscopy is the diffusion coefficient, which is inversely proportional to the polymer radius. In order to get a rough approximation of this radius, the Stokes-Einstein formula was used, which strictly speaking is only valid in the limit of very high dilutions (see Ref. [18]).

[20] R. J. Gordon and C. Balakrishnan, J. Appl. Polym. Sci. **16**, 1629 (1972).

[21] This is also observed in numerical simulations (see Ref. [14]) in which most of the dissipation is observed to be located in layered sheets clearly separated from the filaments.

[22] Our results, however, do not rule out the possibility of simultaneous activity of the polymers in the other small scales of the flow (e.g., boundary layers and dissipative structures).

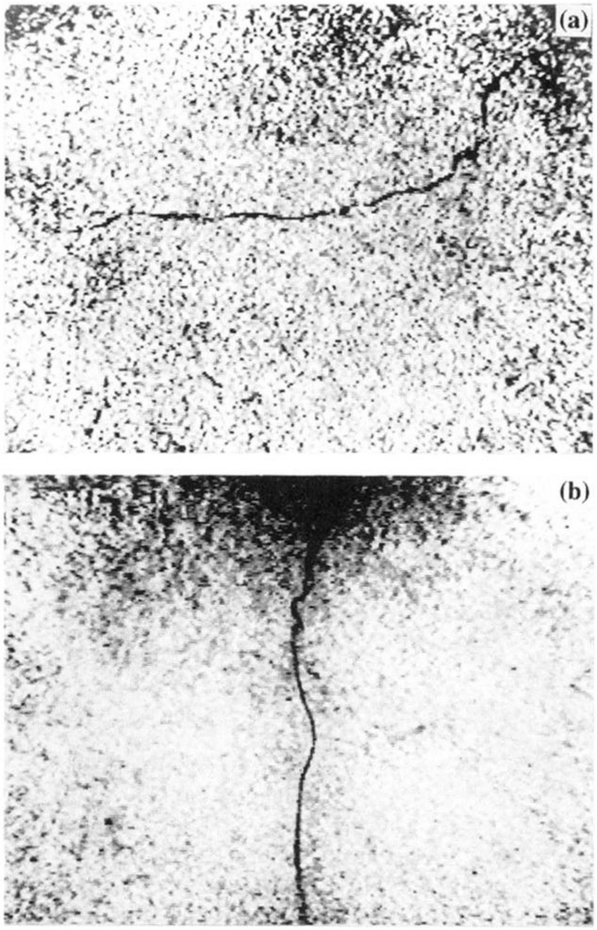

FIG. 2. Two images of high concentrations of vorticity obtained in pure water and observed with small bubbles. The tank is lit with diffuse light from behind: the bubbles appear dark on a light background. (a) A vorticity filament in a turbulent flow (exposure time 0.001 s). (b) The core of an axial vortex below a rotating disk. No photograph after the introduction of polymers is worth showing: not much is left to be seen.