Conference on Turbulence and Interactions TI2006, May 29 - June 2, 2006, Porquerolles, France

On turbulent kinetic energy production in dilute polymer solution flows

A. Liberzon†,*, M. Guala†, B. Lüthi‡, W. Kinzelbach†, A. Tsinober §

†Institute of Environmental Engineering, ETH Zurich, CH-8093 Zurich, Switzerland
‡Risø National Laboratory, Roskilde, Denmark
§Department of Fluid Mechanics and Heat Transfer, Tel Aviv University, Israel
*Email: alexander.liberzon@ifu.baug.ethz.ch

ABSTRACT

We present an experimental study, by means of three-dimensional particle tracking velocimetry (3D-PTV), on the interaction of turbulent flow with dilute polymers in a bulk of a turbulent flow with weak mean shear. We focus on the aspects related to the turbulent kinetic energy (TKE) production, $-\langle u_i u_j \rangle S_{ij}$, such as anisotropy of Reynolds stresses, an alignment between velocity $\mathbf{u}$ and mean rate-of-strain S_{ij}. We compare the water flow to the dilute polymer solution flow, agitated by the frictional forcing of smooth rotating disks. The comparison of the weak mean flow, fluctuating and small-scale turbulent quantities from the water and dilute polymer solution experiments enables a critical examination of the influence of polymers on the TKE production and the related turbulent properties.

INTRODUCTION

Drag reduction, discovered in the mid-40's by Toms [10], is the most extensively known effect of the dilute polymers on turbulent flows. For example, the bibliography of Nadolink and Haigh [7] lists thousands of entries. The main aspects of the phenomenon were reviewed in [3,6], and more recent studies are listed in [8,9], among many others. The phenomenon of drag reduction is observed on the large scales, yet there is a consensus that dilute polymers act mainly on the small scales. It has been shown, for example, by Cadot et al. [1] and also in our study [4], that turbulent flows are altered even if no drag reduction occurs. We devote our experimental study to the interaction of weak mean shear flow with dilute polymers in a turbulent bulk, far from the walls. Our focus is on the aspects of the turbulent kinetic energy (TKE) production, $P = -\langle u_i u_j \rangle S_{ij}$ (where u_i is the fluctuating velocity, $\langle u_i u_j \rangle$ is the Reynolds stresses, and S_{ij} is the mean rate-of-strain tensor), such as anisotropy of Reynolds stresses, the orientation of the velocity vector field in respect to S_{ij}, and others. A three-dimensional particle tracking velocimetry (3D-PTV) system [5,4] was applied. In this method flow tracers are followed in a Lagrangian manner and the fields of velocity and velocity derivatives are measured along the particle trajectories. Properties of the weak mean flow, of fluctuating velocity, and the small-scale quantities such as vorticity, strain and their production terms, were obtained by interpolation of Lagrangian data onto an Eulerian grid.

EXPERIMENTAL SETUP

A detailed description of the 3D-PTV technique can be found in Lüthi et al. (2005) and the facility is shown in details in Liberzon et al. (2005). The experiment was performed in a glass tank, 120

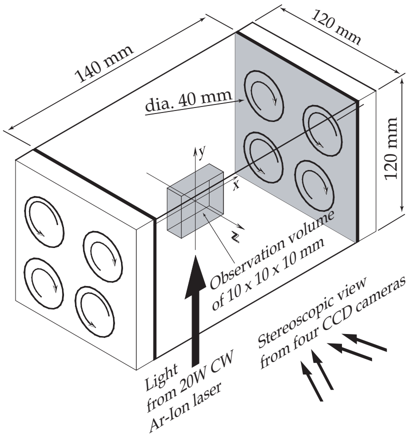

Fig. 1. Schematic view of the experiment, including the forcing scheme.

$\times$ 120 $\times$ 140 mm^3, in water and in 20 wppm dilute solution of poly(ethylene oxide) (POLYOX WSR 301, Dow Inc.). Turbulent flow was maintained by eight counter-rotating disks of 40 mm in diameter, as it is shown in figure 1. The servomotor, operated in a feedback-loop, turned the disks with a constant angular speed of 300 rpm, such to produce in the tank a three-dimensional weak mean turbulent flow. Weak mean flow means that the mean flow quantities were much weaker than their turbulent counterparts. An observational volume was approximately 10 $\times$ 10 $\times$ 10 mm^3, in which about 1000 flow tracers (30 μm neutrally buoyant polystyrene particles) were tracked in each frame. The observational volume was illuminated by an expanded laser beam from a 20 Watt Ar-Ion laser, and diffracted light was sampled simultaneously by four CCD cameras (progressive scan, monochrome, 640 $\times$ 480 pixels, 8 bit per pixel) at a rate of 60 Hz, for a total time of 100 seconds per experiment.

RESULTS AND DISCUSSION

Drag reduction effect in wall-bounded flows was sometimes found to be associated with a significant decrease of the Reynolds stresses, without a substantial reduction of the r.m.s values of the velocity fluctuations [11]. In the other cases of drag reduced flows, the turbulent kinetic energy production was measured and found to be strongly reduced, similar to the viscous dissipation, e.g., Ref. [12]. In our experiment, far from the walls, the turbulent kinetic energy u^2 decreased, as well as its production, $-\langle u_i u_j \rangle S_{ij}$, as it is presented by means of the probability density functions (PDF) in figure 2. Figure 3 depicts the production of turbulent kinetic energy, normalized by the turbulent kinetic energy $\langle u^2 \rangle$ and root-mean-square of the mean rate-of-strain, $\langle S^2 \rangle^{1/2}$, in order to compare the different flow cases by using an invariant (and more objective) quantities. Another closely related invariant

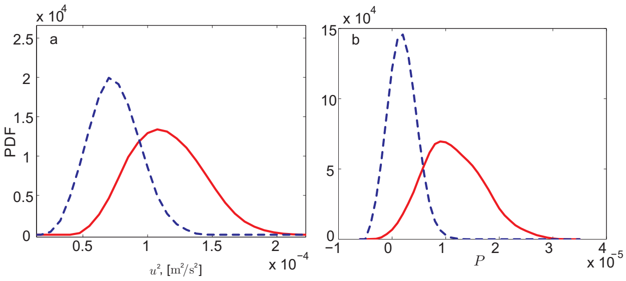

Fig. 2. PDFs of turbulent kinetic energy (left), and turbulent kinetic energy production, $-\langle u_i u_j \rangle S_{ij}$ (right), for water (solid lines) and dilute polymer solution (dashed lines) flows .

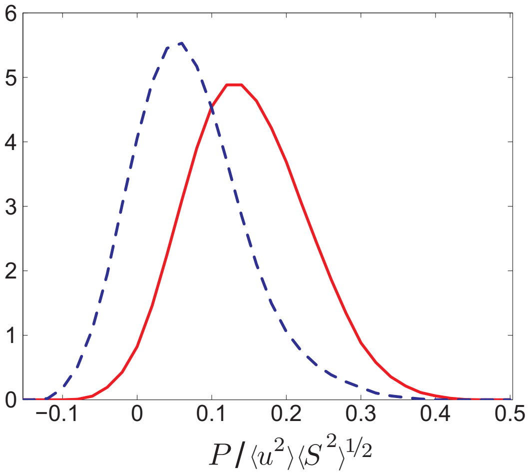

Fig. 3. PDF of the non-dimensional turbulent kinetic energy production, $P = -\langle u_i u_j \rangle S_{ij}$, normalized by the mean turbulent kinetic energy $\langle u^2 \rangle$ and the mean rate-of-strain $\langle S^2 \rangle^{1/2}$, for water (solid line) and polymers (dashed line).

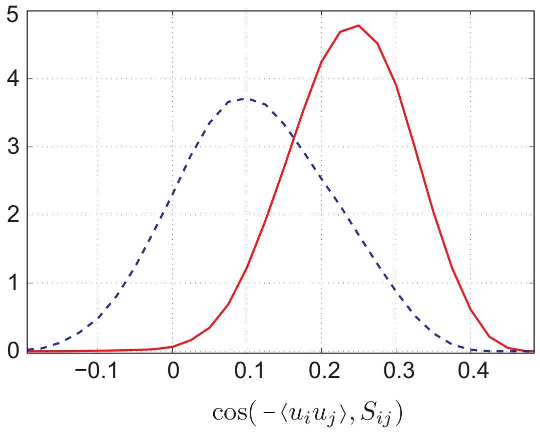

Fig. 4. PDF of the cosine of the angle between the Reynolds stress tensor $-\langle u_i u_j\rangle$ and the mean rate-of-strain tensor, S_{ij}, for water (solid line) and polymers (dashed line).

quantity is an alignment between the Reynolds stress tensor $-\langle u_i u_j\rangle$ and the mean rate-of-strain tensor, S_{ij}. This alignment could be represented by cosine of the angle between two tensors (we calculate the dot product of the two tensors, normalized to their r.m.s values), as it is shown in figure 4. It is noteworthy that this quantity is independent of the strength of the Reynolds stresses and of the mean rate-of-strain.

It is of special interest to analyze the phenomena in the invariant frame of reference, e.g., the eigenframe of the mean rate-of-strain tensor. We follow the idea of Gurka et al. [2], in which the most significant eigen-contribution was observed (both experimentally and numerically) to be associated with the compressing eigenvalue of the mean rate-of-strain tensor, Λ_3^S (λ_3^S). It means, that if the production is decomposed into the three eigen-contributions: $-\langle u_i u_j\rangle S_{ij} = -\langle u^2\Lambda_1^S\cos^2(\mathbf{u},\lambda_1^S)\rangle - \langle u^2\Lambda_2^S\cos^2(\mathbf{u},\lambda_2^S)\rangle - \langle u^2\Lambda_3^S\cos^2(\mathbf{u},\lambda_3^S)\rangle$, then the only significant positive values are added by the third term on the right hand side, because by definition, $\Lambda_1^S > \Lambda_2^S > \Lambda_3^S$, thus $\Lambda_1^S > 0, \Lambda_3^S < 0$. We demonstrate here that the effect of dilute polymers is mainly on the third, *compressing*, eigen-contribution (see figure 5), which ,in some sense, contradicts the wisdom of ”production by *stretching* along the principal strain axis”.

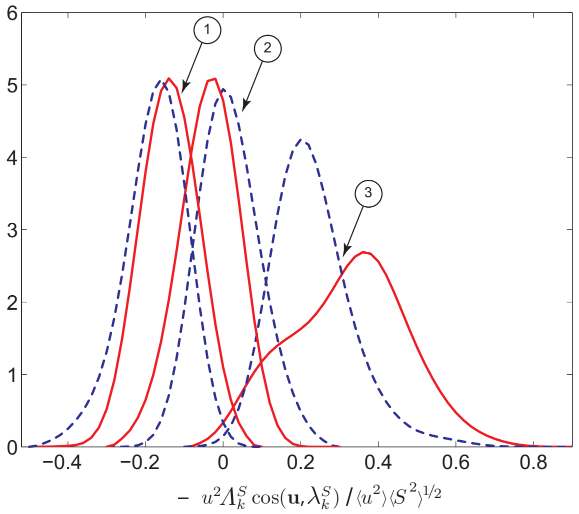

Fig. 5. PDFs of the three contributive terms $P_i = -\langle u^2\Lambda_k^S\cos^2(\mathbf{u},\lambda_k^S)\rangle$ to the turbulent kinetic energy production, $k = 1, 2, 3$, for water (solid lines) and polymers (dashed lines). All terms are normalized by the mean turbulent kinetic energy $\langle u^2\rangle$ and the mean rate-of-strain $\langle S^2\rangle^{1/2}$

We observe also that the fluctuating flow field is oriented differently in respect to the eigenframe of the mean rate-of-strain in figure 6. The PDFs in this figure are of the angle between the velocity vector $\mathbf{u}$ and the eigenvectors Λ_k^S. This is an invariant quantity that demonstrates an effect of dilute polymers on the field of turbulent velocity, irrespective to the magnitudes of velocity vectors or of the eigenvalues of S_{ij}.

CONCLUDING REMARKS

We applied three-dimensional particle tracking velocimetry (3D-PTV) method in order to obtain the direct comparison of the turbulent kinetic energy and its production in a weak mean turbulent flows of water and dilute polymer solution. We observed concomitant changes of the production of turbulent kinetic energy in a turbulent bulk of dilute polymer solution and demonstrated the modified statistics of the different invariant quantities.

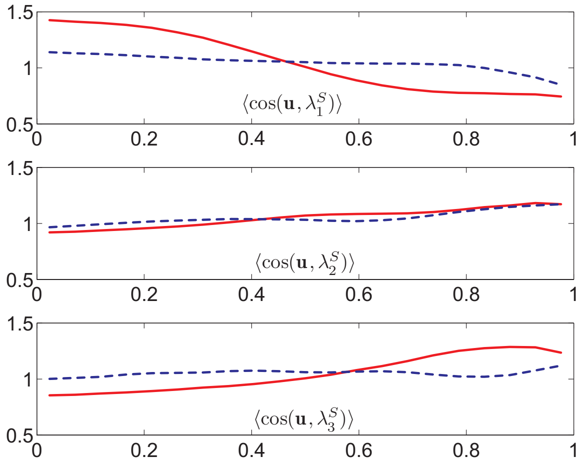

Fig. 6. PDF of the cosine of the angle between the fluctuating velocity vectors, $\mathbf{u}$, and the eigenframe of the mean rate-of-strain tensor, λ_k^S

Our results were obtained in the flow at the rather small Reynolds number. Our belief is that, at least qualitatively, the observed effects should appear in the larger Reynolds number flows.

ACKNOWLEDGEMENTS

This research is supported by ETH research fund, under TH-18/02-4.

BIBLIOGRAPHY

[1] O. Cadot, D. Bonn, and S. Douady. Turbulent drag reduction in a closed flow system: Boundary layer versus bulk effects. *Phys. Fluids*, 10:426–436, 1998.

[2] R. Gurka, G. Hetsroni, A. Liberzon, N. Nikitin, and A. Tsinober. On turbulent energy production in wall bounded flows. *Phys. Fluids*, 16(7):2704, 2003.

[3] A. Gyr and H.-W. Bewersdorff. *Drag Reduction of Turbulent Flows by Additives*. Fluid Mechanics and its Applications. Kluwer, Netherlands, 1995.

[4] A. Liberzon, M. Guala, B. Lüthi, W. Kinzelbach, and A. Tsinober. Turbulence in dilute polymer solutions. *Phys. Fluids*, 17:031707, 2005.

[5] B. Lüthi, A. Tsinober, and W. Kinzelbach. Lagrangian measurement of vorticity dynamics in turbulent flow. *J. Fluid Mech.*, 528:87–118, 2005.

[6] W.D. McComb. *The Physics of Fluid Turbulence*. Clarendon PRess, Oxford, 1990.

[7] R.H. Nadolink and W.W. Haigh. Bibliography on skin friction reduction with polymers and other boundary-layer additives. *ASME Appl. Mech. Rev.*, 48:351, 1995.

[8] P. K. Ptasinski, F. T. M. Nieuwstadt, B. H. A. A. Van den Brule, and M. A. Hulsen. Experiments in turbulent pipe flow with polymer additives at maximum drag reduction. *Flow, Turbulence and Combustion*, 66:159182, 2001.

[9] K.R. Sreenivasan and C.M. White. The onset of drag reduction by dilute polymer additives, and the maximum drag reduction asymptote. *J. Fluid Mech.*, 409:149–164, 2000.

[10] B.A. Toms. Some observation on the flow of linear polymer solutions through straight tubes at large Reynolds numbers. In J.M. Burgers, editor, *Proc. 1st Intl. Congr. on Rheology*, volume Vol. II, pages 135–141. North-Holland, 1949.

[11] A. Tsinober. Turbulent drag reduction versus structure of turbulence. In A. Gyr, editor, *Structure of Turbulence and Drag Reduction*, pages 313–334. Springer, 1990.

[12] M. D. Warholic, M. S. Gavin, and T. J. Hanratty. The influence of a drag-reducing surfactant on a turbulent velocity field. *J. Fluid Mech.*, 388:1–20, 1999.