PAMM · Proc. Appl. Math. Mech. **5**, 545–546 (2005) / **DOI** 10.1002/pamm.200510249

Drag Reduction in Wall Bounded Flows: The Effect of Polymers on the Dynamics of Turbulence

Bettina Frohnapfel*, **Jovan Jovanović, Mira Pashtrapanska,** and **Franz Durst**

Lehrstuhl für Strömungsmechanik, Universität Erlangen-Nürnberg, Cauerstr. 4, 91058 Erlangen, Germany

Experiments in a refractive index matched pipe flow facility were conducted using state-of-the-art laser-Doppler anemometry to study turbulent drag reduction by dilute addition of high polymers. The results were analyzed employing the invariant theory of turbulence. It was thus possible to confirm the major conclusion of preceding theoretical work, namely that the mechanism of drag reduction by long-chain polymers is associated with an increase in anisotropy of turbulence at the wall. Furthermore, theoretical considerations based on the elastic behavior of a polymer and spatial intermittency of turbulence at small scales enabled quantitative estimates to be made for the relaxation time of a polymer and its concentration that ensures maximum drag reduction.

The addition of small amounts of dilute polymers to wall bounded flows can lead to large drag reduction. This phenomena has received much attention since its discovery more than 50 years ago. Nevertheless, detailed knowledge about the chief mechanism for the action of the polymer and its effect on turbulence is not available. In this paper we present experimental investigations of turbulent drag reduction using polymer additives.

The base of this investigation came out of work of Jovanović and Hillerbrand [1] in connection with the flow control of a laminar boundary layer at very high Reynolds numbers. They exploited the fact that theory of turbulent drag reduction in simple, nearly parallel wall-bounded flow can be worked out proceeding from the basic equations that govern the turbulent stresses and by using the turbulence closure based on the application of the two-point correlation technique and invariant theory [2]. The conclusion of this theoretical work is that the most effective way to suppress small-scale fluctuations in the near wall region, and thus to achieve drag reduction, is to force them to be predominantly one-component. To verify whether this implication also holds for polymer drag reduction, an experimental program using state-of-the-art laser-Doppler measuring technique in the refractive index matched pipe flow facility at LSTM Erlangen [3] was initiated. This technique allows accurate experimental data to be obtained deep inside the viscous sublayer, enabling a quantitative basis to be formed for the interpretation of the dynamics of turbulence using the tools of invariant theory [4]. Experiments were carried out for polymer concentrations of 5ppm and 10ppm of a long chain polymer (M $\approx 25\times10^6$ g mol^{-1})[5] with which it was possible to achieve initial drag reduction of 50% and 70% respectively. To quantify drag reduction, which is defined as

$$DR = 1 - \frac{\tau_{w,pol}}{\tau_w}, \tag{1}$$

it was necessary to determine the wall shear stress τ_w. This was accomplished by measuring the mean velocity at a fixed and predetermined position from the wall within the viscous sublayer. In order to analyze the structure of turbulence in a drag reduced flow using invariant theory, the second-order moments are required. The anisotropy tensor is given by

$$a_{ij} = \frac{\overline{u_i u_j}}{q^2} - \frac{1}{3}\delta_{ij} \tag{2}$$

where q^2 is the trace of the Reynolds stress tensor $\overline{u_i u_j}$. Its scalar invariants

$$II_a = a_{ij}a_{ji}, \tag{3}$$

$$III_a = a_{ij}a_{jk}a_{ki}. \tag{4}$$

are used to quantify all possible states of turbulence in a bounded region. Within this anisotropy invariant map (AIM) all realizable turbulence can be found [6].

Using existing DNS data sets it can be shown that for the limiting state close to a solid boundary the anisotropy tensor can be based on axial and tangential velocity fluctuations only without introducing a remarkable error. Therefore, besides mean velocity the fluctuations in axial and tangential direction were measured. Our experimental results, plotted on the AIM are shown in figure 1 (a and b) along with the corresponding values of turbulent drag reduction (c). As time increases the polymer disintegrates due to mechanical straining during operation of the facility so that its effect on turbulence, namely drag reduction, reduces with time. The related points on the AIM show a movement downwards with time, which corresponds to a reduced level of anisotropy for decreasing drag reduction. Thus, high values of drag reduction can be related to highly anisotropic states of turbulence. Based on these measurements it is concluded that polymers use the theoretically identified

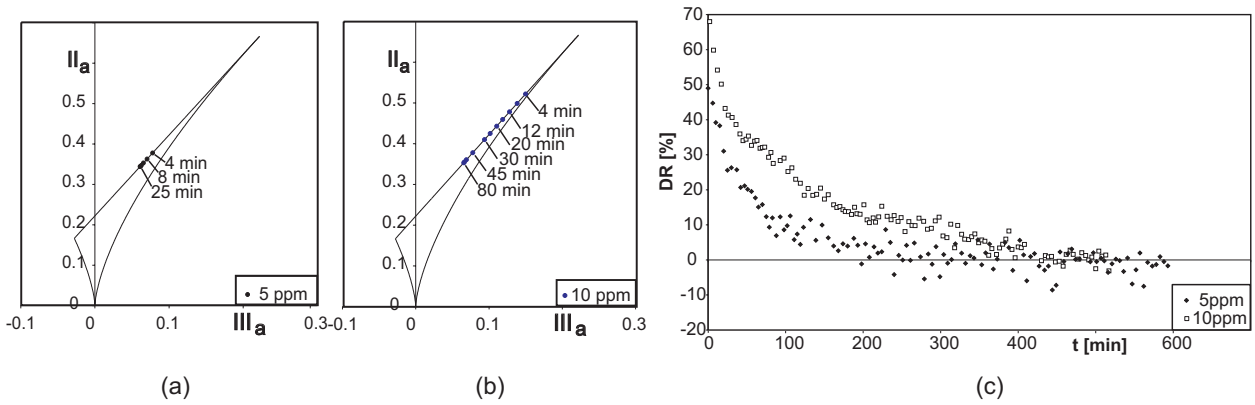

Fig. 1 Measurement results for polymer concentrations of 5ppm (a) and 10ppm (b) plotted on the anisotropy invariant map. In comparison with the corresponding drag reduction (c) it is obvious that higher drag reduction corresponds to a higher level of anisotropy at the wall.

way for most effective drag reduction by forcing turbulence at the wall to the a highly anisotropic state. The question how polymers in very low concentrations can achieve such a remarkable effect can be answered considering the characteristic time scales of polymer and turbulence. The former is basically determined by the molecular weight of the the polymer, whereas the latter is a function of Reynolds number. The smallest time scales in the turbulence cascade decrease with increasing Reynolds number. If they become of the same order as the polymer time scale, interaction between the two is possible. In a conceptual scenario the polymer is forced to unroll and eventually stretch in the mean flow direction due to the large velocity gradients close to the wall. The stretched polymer will in turn influence the interacting turbulence scale so that they are also stretched in the mean flow direction. This increase in length scales can be shown to lead to an increase of turbulent anisotropy as it is seen from the experiments.

Based on this scenario it is possible to provide consideration of the two most important issues related to maximum turbulent drag reduction for pipe flows: determination of the relaxation time of a polymer and its concentration. The polymer starts to act as soon as the smallest time scales in the turbulent flow have reached the characteristic time scale of the polymer. Since the polymer has a certain distribution in molecular weight the effect of drag reduction increases until the smallest turbulent time scale has activated the smallest polymer time scale (i.e. the lowest molecular weight). Knowing the turbulence characteristic of a given flow it is therefore now possible to determine the required polymer weight for maximum drag reduction. The second question that arises in this respect is how much of the polymer is actually needed. It is well known that polymer drag reduction can be achieved with a few ppm on polymer. Assuming that we only need enough polymer to restructure the smallest scales of turbulence - their change will reflect in the entire turbulence cascade - an approximation of required polymer concentration is based on the volume occupied by the smallest turbulence scales (that only occur intermittently) in comparison to the total fluid volume. Since the smallest turbulence scales decrease in size as the Reynolds number increases but their intermittent spacing remains constant, it is predicted that the required polymer concentration for maximum drag reduction decreases with increasing Reynolds number. These estimates are in very good agreement with existing test series for conditions of maximum drag reduction [7, 8].

References

[1] JOVANOVIĆ, J. AND HILLERBRAND, R. 2005 On peculiar properties of the velocity fluctuations in wall-bounded flows. *Thermal Science*, in press.
[2] JOVANOVIĆ, J. 2004 *The Statistical Dynamics of Turbulence*, Springer-Verlag, Berlin-Heidelberg.
[3] DURST, F., JOVANOVIĆ, J. AND SENDER, J. 1995 LDA measurements in the near-wall region of a turbulent pipe flow. *J. Fluid Mech.* **295**, 305–335.
[4] LUMLEY, J.L. AND NEWMAN, G. 1977 The return to isotropy of homogeneous turbulence. *J. Fluid Mech.* **82**, 161–178.
[5] KOSKINEN, K.K. 2004 On investigating turbulent reactive flows: case studies of combustion and drag reduction by polymer additives. Ongoing Ph.D. thesis, Tampere University of Technology, Tampere, Finland.
[6] LUMLEY, J.L. 1978 Computational modeling of turbulent flows. *Adv. Appl. Mech.* **18**, 123–176.
[7] DURST, F., HASS, R., INTERHAL, W. AND KECK, T. 1982 Polymerwirkung in Strömungen-Mechanismen und praktische Anwendungen. *Chem.-Ing.-Tech.* **54**, 213–221.
[8] TILLI, M., MAARANEN, J., TIMONEN, J., KATAJA, M. AND KORPPI-TOMMOLA, J. 2003 Effect mechanisms of DR molecules. Technical Report, University of Jyväskylä, Finland.

* Corresponding author: e-mail: bfrohnap@lstm.uni-erlangen.de, Phone: +49 9131 85 28278, Fax: +49 9131 85 29503