Turbulent drag reduction by polymers

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Abstract
The reduction of turbulent energy dissipation by addition of polymers is studied
experimentally. We first address the question of where the action of the
polymers is taking place. Subsequently, we show that there is a direct correlation
of drag reduction with the elongational viscosity of the polymers. For this, the
reduction of turbulent energy dissipation by addition of the biopolymer DNA
is studied. These results open the way for a direct visualization study of the
polymer conformation in a turbulent boundary layer.

Turbulence is a problem of immense practical importance, but some of the most basic questions
about it still remain to be answered. One very interesting problem that remains open is that of
turbulent drag reduction. The spectacular reduction of turbulent energy losses by the addition
of small amounts of certain polymers is a phenomenon that is still ill understood, in spite of the
enormous attention the subject has attracted over the past few decades [1]. Classically, drag
reduction is observed in pipe flow experiments by a decrease of the friction factor measured
with the pressure drop along the pipe. Experimentally, it has been established that flexible
polymers such as polyethylene oxide and polyacrylamide offer the best 'value for money'
in the sense that very small quantities (a few parts per million by weight) already lead to a
significant reduction of the turbulent energy losses. However, it is not clear what the action of
the polymers is on the turbulent flows. The two principal questions that need to be answered
are:

(i) Where in the turbulent system do the polymers intervene (and how can we describe the
flow field that interacts with the polymers)?
(ii) How do the polymers, in turn, modify this flow field (and how can these modifications be
correlated with the dynamics of the polymer chains)?

Question (i) has been the subject of intense debate recently. The general consensus has been for a long time that the polymers intervene in the turbulent boundary layer close to the wall. However, in a recent experiment heterogeneous drag reduction was observed by injecting a polymer solution in the centreline of a pipe, apparently before the polymer had time to travel the distance from the centreline to the tube wall [2]. Subsequent experiments revealed, however, that the polymers did in fact reach the near-wall region when heterogeneous drag reduction was observed, leading again to the (generally accepted) inference that drag reduction is, in fact, a boundary layer effect [3]. We recently provided a very simple experimental demonstration of this conclusion that we will discuss below [4].

The second question, how the polymers modify the flow field and how these modifications are related to the dynamics of the polymer chains, has proved more difficult to answer. Most attempts to understand the effect are based on the fact that the polymer molecules, coiled in spherical shape at rest, can be uncoiled and stretched under the stress that the fluid exerts on them [5]. The key macroscopic property of these solutions that is known to be significantly different from that of the solvent is its elongational viscosity. The elongational viscosity describes the resistance of a liquid to an elongational flow [6]. In Newtonian liquids the elongational viscosity is just given by the shear viscosity times a geometrical factor of three, the Trouton ratio. The addition of a small amount of polymers to the solvent does not change the shear viscosity significantly; however, the elongational viscosity may increase by several orders of magnitude [6]. Therefore, drag reduction is usually attributed to the elongational viscosity; however, the precise connection remains unclear. We will discuss the relation between drag reduction and the elongational viscosity below [7].

1. Is drag reduction a boundary layer or a bulk effect?

In experiments on turbulence, flows are generally driven either at constant velocity or at constant force. For instance, pipe flows are realized by either setting the flow rate (constant velocity forcing) or the pressure gradient (constant force). In both cases, the energy injection is not constant, and the injected power randomly fluctuates due to the feedback of the produced turbulence on the forcing. The injected power is the quantity that we measure here.

We have previously described the experimental cell in detail [4]. The turbulence is generated in a closed cylindrical cell, of volume 11 litres, between two counter-rotating stirrers of radius $R = 8.75$ cm spaced two disc diameters apart. A DC servomotor regulated by a servo-amplifier (Parvex) drives each stirrer independently. The motors are configured to keep the discs rotating at a given rotation frequency, independently of the torque exerted by the turbulence on the discs. This is done by using a tachymetry feedback loop, a regulation system that adapts the torque delivered by the motors to maintain the imposed angular velocity. The time response of the control loop is 0.05 s. For lower frequencies, the image of the current at the output of the feedback loop gives an instantaneous measurement of the torque. The mechanical power supplied by the motors is simply given by the product of the current image at the feedback output (i.e. the torque) to the tachymetry signal (i.e. angular velocity). The total power injected into the flow is computed by summing up the contribution of each servomotor's mechanical power and subtracting the power due to the torques of friction losses, which were measured independently in the empty cell (full of air), as well as the inertia of the forcing devices, for which a correction is necessary. In the following, we use the injected power per unit mass ε.

We use two types of stirrers: we have a pair of smooth discs and discs to which baffles have been added. For both cases, we define the integral Reynolds number as $Re = \Omega R^2 / \nu$, where R is the radius of the discs and ν the kinematic viscosity of the fluid. As follows from the well-
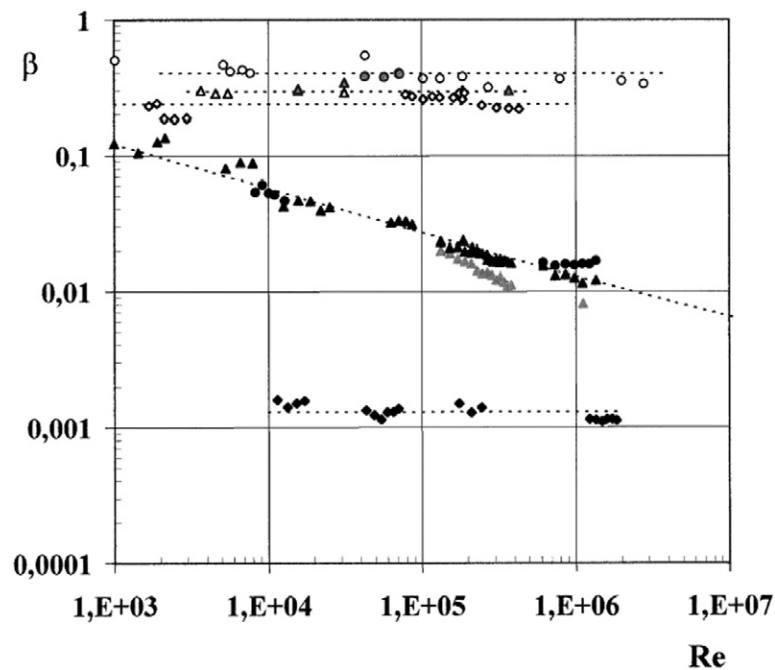
Figure 1. Power number for the two different forcing schemes versus the Reynolds number. The open symbols are results obtained with baffled discs, and the full symbols are results obtained with smooth discs. *Measurements in water (black and white symbols)*: for the forcing with baffled discs the power number is constant, in agreement with Kolmogorov scaling for over three decades, while for the case of the smooth forcing, the power number follows a $-1/3$ power law behaviour in the Reynolds number. *Measurements in the polymer solution (grey symbols)*: for the forcing with baffled discs, all the measurements in water are identical to measurements in the polymer solution: no drag reduction is observed, independently of the Reynolds number. For the case of smooth forcing a significant drag reduction of approximately 30% is found.

known Kolmogorov scaling arguments [8], the turbulent power dissipation P (far from any boundary layer) should scale as $P \propto mU^3/L$, where m is the total mass of the fluid; $U \propto \Omega R$ and R are respectively the large scale velocity and the large scale length of the turbulence. The most important point of this scaling argument is that the dissipation is *independent of the viscosity of the fluid*: all the energy that is injected at the large scale will dissipate viscously, but the energy injection rate is independent of the viscosity. For our experiment, the power dissipated, according to the Kolmogorov argument, can then be written as [4]

$$P_{\text{bulk}} \propto \rho \Omega^3 R^5.$$

We thus introduce the power number β, defined as the dissipated power rescaled by the Kolmogorov scaling factor:

$$\beta = P/\rho \Omega^3 R^5.$$

Figure 1 shows the measurement of β [4]. The Reynolds number was varied by changing both the angular velocity and the viscosity using different glycerol solutions. Also, a smaller experimental cell was used. The results between the different set-ups agree very well. We find that for the forcing with baffles, the power number β is, within experimental error, a constant over three decades in the Reynolds number. This is exactly what one would expect

from the Kolmogorov arguments presented above: the dissipated power depends neither on the viscosity of the fluid nor, consequently, on the viscous boundary layers. These results thus show that the forcing of the flow with baffles is completely inertial.

For the 'smooth' discs (without baffles), on the other hand, the dissipated power does depend on the viscosity or Reynolds number. The power number decreases continuously with increasing Re; on the log–log scale of figure 1, an approximately linear decrease is found. The experiment then shows that β follows a power-law behaviour in the Reynolds number with a power of $-1/3$. Thus, for the smooth forcing the power number depends on the viscosity and on the viscous boundary layer. This decrease with the Reynolds number is analogous to the Re-dependence of the friction factor in pipe flow experiments: it is due to a decrease of the thickness of the viscous boundary layers with increasing Reynolds number.

The polymer we use is the well-known flexible polymer Polyox (polyethyleneoxide, PEO); different molecular masses are available from Union Carbide. For the experiments described below, we use Polyox WSR301 ($M_{avg} = 4 \times 10^6$ amu), which is the most effective drag-reducing polymer known today. The overlap concentration was determined from viscosity measurements to be 250 weight parts per million (wppm). The concentrated polymer solution is injected directly through a little pipe through the cell wall in the middle of the cell. After injection and mixing, the resulting concentration of polymers is 30 wppm. For this low concentration, the viscosity of the fluid is practically the same as the solvent viscosity (water). A measurement of the shear viscosity for different shear rates reveals that no appreciable non-Newtonian behaviour can be observed, and that the viscosity is practically equal to that of pure water [9]. For typical experimental parameters, we find that after injection of the polymers, a new stationary state is reached with dissipation smaller than that for water, the power dissipated being reduced by roughly 30%.

For the forcing with baffles, on the other hand, our results show that there is no difference between the power dissipation for the water and the polymer solution. We also performed the same experiment with lower and higher rotation speeds of the discs: no drag reduction effect could be detected. This is depicted in figure 1, where we show the overall energy dissipation as a function of the Reynolds number with and without the polymers.

In conclusion, drag reduction occurs only in boundary layer driven turbulence: if no boundary layers are present, indeed no drag reduction is observed upon the addition of polymers. This implies that it is the way the turbulence is generated by the boundary layers that is altered by the addition of polymers. Another, related, remark is that only if the turbulence is generated inertially (as is the case for the forcing with baffles) does it obey the Kolmogorov hypothesis that the dissipation is independent of the viscosity. Trying to modify the Kolmorogov arguments to obtain drag reduction therefore seems a hopeless task, as there is no drag reduction in 'Kolmogorovian' turbulence.

## 2. Relation between drag reduction and elongational viscosity

The key macroscopic property of dilute polymer solutions that is known to be significantly different from that of the solvent is its elongational viscosity. Therefore, drag reduction is usually attributed to the elongational viscosity; however, the precise connection remains unclear. The elongational viscosity describes the resistance of a liquid to an elongational flow. In Newtonian liquids the elongational viscosity is just given by the shear viscosity times a geometrical factor of three, the Trouton ratio [10]. The addition of a small amount of polymers to the solvent does not change the shear viscosity significantly; however, the elongational viscosity can increase by several orders of magnitude. Taking an elevated elongational viscosity

into account, a qualitative explanation of drag reduction has been given by Landahl [5]: he suggests that the elongational viscosity can suppress the occurrence of streaks—regions of flow with a highly elongational part—in the turbulent boundary layer. These boundary layer instabilities lead to 'blobs' of fluid that are ejected from the boundary layer into the bulk of the liquid and which generate the turbulence. However, others [11] provide experimental evidence that low speed streaks become more important in the boundary layer upon polymer addition and that the wall normal enstrophy is reduced. It is in any case not clear how to define these 'blobs' of fluid, so that the Landahl theory remains qualitative.

The more important point is that, to our knowledge, an explicit experimental proof of the relation between the elongational viscosity of a given polymer solution and its ability to cause turbulent drag reduction was still missing until recently [7], mainly because the determination of the elongational viscosity of drag-reducing polymer solutions has proved difficult [6, 12]. In order to see whether such a relation exists, we studied both the elongational viscosity and turbulent drag reduction of polymers that allow us to tune their chain flexibility. The large elongational viscosity of dilute polymer solutions is usually attributed to a resistance to stretching of the polymer chains in an elongational flow field. Therefore, flexible polymers should have a higher elongational viscosity. If in addition the phenomenon of drag reduction is indeed related to the elevated elongational viscosity, drag reduction should also increase with increasing chain flexibility. We show here that this is indeed the case using polyelectrolytes, for which the chain flexibility can be tuned by the addition of salt to the solvent [7]. In this way the chain flexibility is altered *without* changing either the polymer chemistry or the chain length, the effects on drag reduction of which are still ill understood. The first polyelectrolyte solutions we used were aqueous solutions of double stranded λ-DNA (48.5 bp) at the overlap concentration c^* of 40 wppm. Our solutions contained 10 mM TRIS and 1 mM EDTA buffer for solution stability. The NaCl concentration of these solutions was varied from 0 to 10 mM, changing the persistence length of the polymer by a factor of three. The second polyelectrolyte used was 40 wppm hydrolyzed polyacrylamide (HPAA) with a molecular weight of 5×10^6 amu in water with NaCl concentrations varying from 1 to 18 mM.

To investigate turbulent drag reduction we measured the drag of a turbulent flow of the different liquids in a Couette cell with a gap $d = 1$ mm. These measurements were performed on a standard (Reologica Stresstech) rheometer. The rheometer was driven in controlled stress mode, and drag reduction (DR) is defined as the normalized difference of the torque exerted on the inner cylinder by pure water and by the polymer solution respectively at same Reynolds number, defined as $Re = \frac{\rho \Omega R d}{\eta}$, R being the radius of the inner cylinder. For a constant applied stress of 8 Pa, the highest value that could be obtained with our rheometer, this yields a Reynolds number $Re = 2000$.

The DR as a function of the Reynolds number is shown in figure 2. Both for the DNA and for the PAA solution, the DR is found to depend on the salt concentration in the solvent: drag reduction increases with increasing salt concentration. For the HPAA solution, for a salt concentration of 18 mM, a DR of approximately 20% is found. The more surprising result is that for the lowest salt concentration no DR is observed, but rather a drag enhancement. This strongly suggests an important effect of the flexibility of the polymer chains on the DR. As can be observed in the figure, there is a certain critical salt concentration (i.e., flexibility) necessary to observe DR. For the DNA solution the results are qualitatively the same as for the HPAA, but the effects are less pronounced. For all the solutions, we observe an increase of DR with increasing Re, as also observed in pipe flow. The DR is positive for the highest salt concentrations, but again goes from negative to positive for the lowest salt concentrations: the drag enhancement turns into a drag reduction when the Reynolds number is increased. We checked that this is not due to our use of the Couette cell, or the very moderate Reynolds
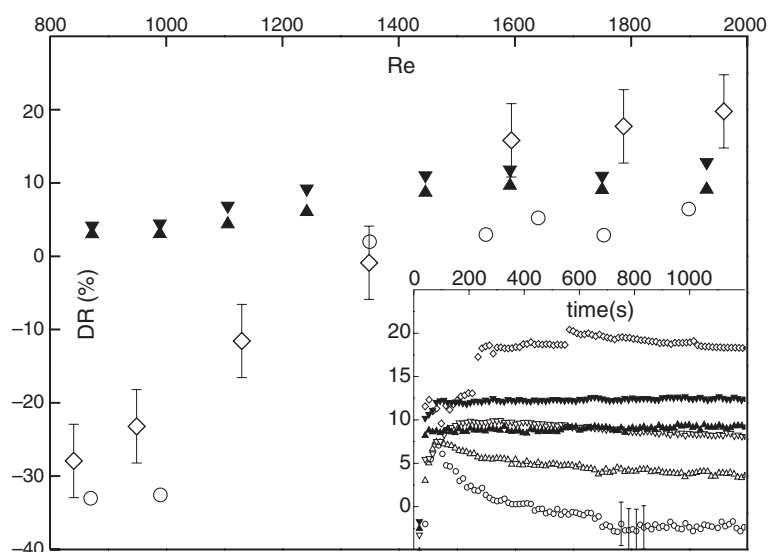
Figure 2. Turbulent drag reduction DR as a function of the Reynolds number *Re*. Inset: drag reduction as a function of time at a constant stress of 8 Pa. Open symbols: HPAA 1 mM NaCl (circles), 2 mM (up triangles), 7 mM (down triangles), 18 mM (diamonds). Filled symbols: DNA 0 mM NaCl (up triangles), 10 mM (down triangles).

numbers employed here, by repeating the experiments for PAA in the turbulence cell described above: these high-Reynolds number experiments gave very similar results. The interesting dependence of the DR on the Reynolds number *Re* is still completely unclear and opens many questions for further investigation, both on the quantitative explanation of turbulent drag reduction, and on the transition to inertial turbulence in the presence of polymers, which in principle may generate supplementary instabilities that are elastic in origin.

Having measured the effect of salt on the drag reduction, we now turn to the elongational viscosity. As the velocity fluctuations in turbulence are violent, and rapidly change direction, it is unlikely that the polymer extension in such flows reaches a steady state. The pertinent experiment is therefore to study incipient (start-up) elongational flow, and measure the response of the polymer solutions to that. In order to measure the dynamic elongational viscosity $\eta_e(t)$ of our solutions we study the detachment process of a droplet of a dilute polymer solution from a capillary [12]. The addition of a small quantity of flexible polymers to water inhibits the finite time disruption process of the droplet, and instead a cylindrical filament is formed between the capillary and the droplet. The flow profile in the filament is purely elongational, and by balancing the surface forces to the elastic stresses, the elongational viscosity $\eta_e(t)$ can be extracted from the measured filament diameter $h(t)$ [12].

It is therefore now possible to relate the drag reduction directly to the elongational viscosity. The result is shown in figure 3. We plot the drag reduction for a given Reynolds number as a function of the elongational viscosity η_e at a Hencky strain (total deformation undergone in the flow) of 1. The DR is shown to increase monotonically with the elongational viscosity for a given solution and the data for the different polymers collapse together, demonstrating that indeed the elongational viscosity is the pertinent quantity to account for the DR. As far as we can tell, this is the first explicit demonstration that the turbulent drag reduction is directly connected with the elongational viscosity of a polymer solution [7].
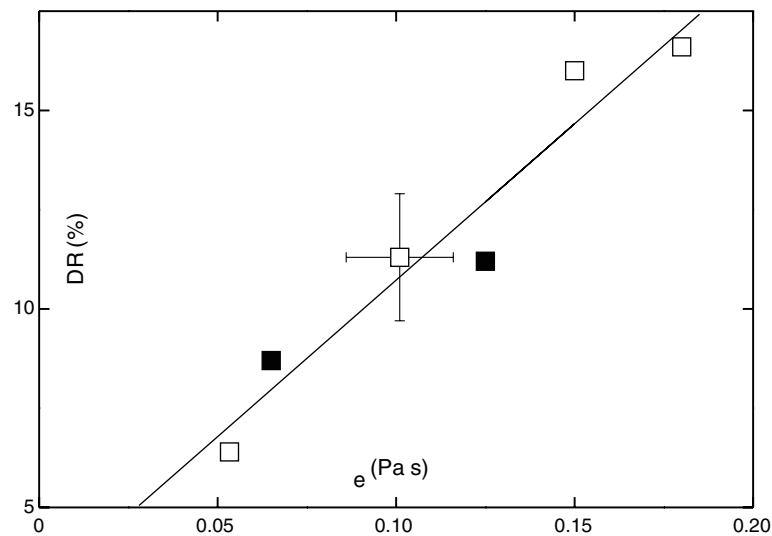
Figure 3. Drag reduction DR at a Reynolds number of 1400 as a function of the elongational viscosities of the aqueous polymer solutions for different salinities at a Hencky strain of 1. To allow for a comparison between samples with different shear viscosities, the Reynolds number is calculated using the laminar shear viscosities of the polymer solutions at a shear rate of 2000 s^{-1}. Filled squares: DNA-solutions; open squares: HPAA solutions.

3. What is next?

These results, especially those on DNA, open the way to a microscopic understanding of both the enormous elongational viscosity dilute polymer solutions can have, and the surprising results thereof: turbulent drag reduction. It has recently become possible to observe the deformation of the polymer chains due to flow of single DNA molecules using fluorescence microscopy. Performing such an experiment on the filaments would allow relating the extension of the individual polymer chains to the macroscopic stresses the chain extensions generate. If subsequently the polymer conformation is visualized in a turbulent boundary layer, an estimate of the extra stresses in the boundary layer could be obtained, which could be the key to the understanding of this phenomenon. These experiments are in progress.

Acknowledgments

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