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Modification of a vortex street by a polymer additive

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A Kármán vortex street is created in a flowing soap film by a rod penetrating the film. The velocity field generated by this rod is modified by the addition of the polymer polyethylene oxide having a molecular weight of $5 \times 10^6$ and a concentration of 30 wppm. The r.m.s. velocity fluctuations behind the rod are strongly suppressed by the polymer additive and the power spectrum of the velocity fluctuations is modified as well. The experiments show that the polymer additive decreases the rate at which energy is injected into the flow. The measurements further indicate that the polymer introduces an elongational viscosity term into the Navier–Stokes equation. © 2001 American Institute of Physics. [DOI: 10.1063/1.1347962]

I. INTRODUCTION

It has long been known that the drag force exerted by a fluid flowing in a pipe is markedly larger if the fluid is turbulent rather than laminar. Some 50 years ago it was discovered that the addition of a very small amount of a long chain polymer to the turbulent fluid has the effect of suppressing this excess drag. This phenomenon is still not understood. While large on an atomic scale, the polymer molecules are much smaller than the smallest eddy sizes one expects to find in the turbulent fluid, at least when the molecules are in their relaxed coiled-up state. The problem is doubly complex because it involves two imperfectly understood subjects, i.e., the rheology of the molecules when they are exposed to shear and the phenomenon of turbulence itself.

The present experiment was undertaken to reduce the complexity of the problem by examining the effect of a polymer additive on a flow that is only weakly turbulent. The phenomenon being studied here is the influence of the polymer additive on vortex shedding in a quasi-two-dimensional system, namely a rapidly flowing soap film, through which a rod has been thrust. At the onset of vortex shedding, the turbulence is very weak in the sense that it can be described by a language appropriate to nonlinear systems in which relatively few degrees of freedom are excited. Drag reduction by a polymer additive in this simple type of flow has been studied for many years.

One might hope that drag reduction and the suppression of turbulence in the bulk fluid are manifestations of the same phenomenon. However, a definitive experiment by Cadot et al. shows that this hope is not realized. While it is observed that the polymer additive suppresses small-scale velocity fluctuations in the turbulence far from the container walls, drag reduction is due to the alteration of the shear layer near the boundaries. The experiment reported here probes the effect of a polymer additive on a boundary layer.

Vortex shedding, with which we are concerned here, refers to the generation of pairs of vortices by a cylindrical rod in a water tunnel or wind tunnel where the flow is otherwise uniform. Boundary layer separation occurs at a moderate mean flow velocity $U_f$ and leads to the creation of recirculating vortices. The vortices remain attached to the rod due to a balancing of shear and pressure forces. As $U_f$ is increased, a shear instability behind the vortices causes the flow to become periodic. When a critical value of $U_f$ is reached, the flow becomes unstable, causing the vortices to detach from the rod. The vortices that peel off the rod are in the form of staggered, counter-rotating pairs that are convected downstream.

In our soap film measurements, laser Doppler velocimetry (LDV) was used to measure the local velocity at various points below the rod. The vortex street produced by this rod can also be observed by eye because the vortices give rise to variations in the film thickness, which has an average value of a few micrometers. The thickness variations produce an interference pattern which is displayed in Fig. 1. The flow, which is downward in the experiment, is from left to right in the figure. The rod, which is perpendicular to the film, may be seen at the left. The mean vertical flow speed is 1.7 m/s. The polymer concentration is 0 in Fig. 1(a) and 30 wppm in Fig. 1(b). The molecular weight of the polymer used in most of these experiments is $M = 5 \times 10^6$.

In spite of its low concentration, the polymer additive strongly disorders the regularly shed vortices seen in Fig. 1(a). A discussion of these figures is deferred to Sec. IV.

A measurement of the time dependence of $v_y(t)$, the component of velocity perpendicular to the flow direction, is shown in Fig. 2. The power spectrum, $S(f)$, of $v_y(t)$ is sharply peaked at the shedding frequency, $f = f_s$.

One effect of the polymer is its reduction of the kinetic energy contained in the velocity fluctuations. The measurements show that the polymer also lengthens the boundary layer behind the rod. We believe this stretching effect arises from the elongational viscosity, which is appreciable even at such low polymer concentrations, provided the molecular weight is high. The elongational viscosity is known to depend strongly on the molecular weight of the polymer. The present experiments show that a polymer additive of molecular weight $5 \times 10^6$ strongly alters vortex shedding, whereas a polymer of much higher concentration but having a molecu-
lar weight of $3 \times 10^5$ has no effect. This observation gives further credence to the idea that the elongational viscosity is implicated in the effects that are seen. The high molecular weight polymer also broadens the otherwise sharp frequency power spectrum $S(f)$.

The strong effect of a polymer additive on vortex shedding has recently been seen in a vertical water channel. In that experiment a polymer solution of relatively high concentration was injected into the flow through the holes in the cylinder that generate the vortex street. A dye in the injected solution showed that the polymer alters the lateral spacing of the chain of counter-rotating vortices and produces other visible effects as well.

Details of our experiment are presented in Sec. II and the results are given in Sec. III. Section IV is a discussion of our findings, and the work is summarized in Sec. V.

II. EXPERIMENT

The sheet of flowing soap film is formed between a pair of thin nylon lines suspended vertically and held taut by a weight at the bottom. The separation, $W$, of these lines, is 5 cm, and the height of the channel is roughly 2 m. The mean film thickness $h$ is in the range $2<h<5 \, \mu m$. At the top of the soap film tunnel is a reservoir of soap solution which is fed through a valve to the vertex where the wires join. The mean flow speed is adjustable in the range $0.5 \, m/s < U_f < 2.5 \, m/s$.

The spent soap solution is collected in a second reservoir at the bottom. The polymer-containing solution was not recirculated back to the top reservoir with a pump to avoid rupturing the polymer chains as the solution flows through the pump.

In most vortex shedding experiments the control parameter is the Reynolds number, defined as $Re = U_f d/\nu$, where $\nu$ is the kinematic viscosity of the flowing medium. In a soap film experiment, $\nu$ is a function of the thickness and is therefore not equal to the viscosity of the bulk mixture. Rather, it has contributions from the surfactant layers on the film surfaces and the solution in the interior, which is mainly water.

The onset of vortex shedding in these soap films appears at $U_f = 0.5 \, m/s$. In three-dimensional flows this onset corresponds to $Re = Re = 47$. The present measurements were made at $U_f = 2 \, m/s$. In our soap films this corresponds to a Reynolds number of roughly 400.

In this experiment the rod was made of glass, its diameter $d$ being fixed at 2 mm in all the experiments. A clean glass rod is wetted by the soap solution, causing the film thickness to increase in an annular region that extends radially for a fraction of a millimeter. This local thickness increase is roughly a micrometer. The same visual vortex street pattern seen in Fig. 1(a) is generated even when the rod is made of a nonwetting material such as teflon.

The mean vertical flow speed of the soap films varies measurably with the distance from the upper vertex. For approximately the top third of the channel height the film is accelerating, and for the bottom third it is decelerating. All measurements were therefore made in the central third of the channel. The addition of the polymer did not have an appreciable effect on the spatial evolution of the mean flow speed.

The desired concentration of the PEO solutions was achieved in two successive dilutions, as described elsewhere. Care was taken to ensure that the polymer additive had ample time to fully dissolve in the neat 1% soap solution, the detergent being Dawn.

Measurements were taken using a two-probe TSI laser Doppler velocimeter. With one of the probes $U_f$ was measured 5 cm above the rod. The film was seeded with polystyrene latex particles having a diameter $d = 1 \, \mu m$, their concentration being $\sim 50 \, \mu l$ per liter of soap solution. At this concentration the counting rate was maximized.

A fast Fourier transform (FFT) program was used to extract the power spectra $S(f)$ from the velocity record $v_y(t)$. Because the seed particles pass through the observation point at irregularly spaced intervals, a standard binning procedure is used to obtain a record of velocity at equally spaced time intervals. The spectra were determined from a set of 200,000 points, which required making measurements for several minutes.

The viscosity $\eta$ of the bulk soap–water–polymer solutions was measured in a Brookfield viscometer operating at 4 Hz. As the polymer concentration was increased from 0 to 200 wppm, $\eta$ increased from 1.1 to 1.4 cp. When glycerol was added to the mixtures to ensure that all the measurements were made at the same value of $\eta$, the recorded spectra were the same as the $S(f)$ measured with the glycerol absent. Therefore glycerol was never added to the solution.

III. RESULTS

The dominant effect of the polymer can be understood from Figs. 2 and 3. Shown are the time-averaged longitudi-
FIG. 2. Time-averaged longitudinal velocity measured directly below the rod vs the downstream distance. The open and closed circles show data for the polymer-free and polymer-containing films. The ordinate and abscissa are expressed in dimensionless units, with \( U_f \) the mean vertical flow speed well above the rod.

FIG. 3. The normalized, time-averaged transverse velocity vs the transverse distance measured from the rod axis. These measurements were taken at point 2 mm downstream from the rod.

and for soap solutions containing 30 wppm of PEO. Measurements for concentrations of 0 and 30 wppm are denoted by closed and open circles, respectively, in all figures presented here. The dashed and solid lines are a guide to the eye. The velocities will be designated by the subscripts 0 and 30 for \( c = 0 \) and \( c = 30 \) wppm.

From Fig. 2 it is seen that \( U_0(X) \) is negative for 0.1 \( \leq X/d \leq 0.8 \). The negative sign is indicative of the presence of the vortices before they detach from the rod. For greater values of \( X/d \), \( U_0(X) \) rises, reaching a (local) maximum at \( X/d \approx 3 \), before rising toward the mean flow velocity far downstream. In contrast, \( U_{30} \) for the polymer-doped solution remains negative out to \( X/d = 3 \) and then slowly increases monotonically toward the mean flow velocity \( U_{30} = U_f \). At \( X = 0 \), \( U \) must become 0, but a slight horizontal misplacement of the velocity probe prevents this limit from being reached.

The two curves in Fig. 2 appear to be of the same form, aside from a stretching of the abscissa in the polymeric flow. We can explain this stretching by assuming that the polymer alters the elongational viscosity of the fluid. The elongational viscosity \( \eta_{el} \) is defined by \( \eta_{el} = \frac{1}{X_t} \frac{\partial \mu}{\partial x} \), where the left and right sides are time averages over very many vortex shedding periods.

A measurement of the flow rate, \( Q \), of the soap film through the channel with the polymer present and absent showed that the polymer reduces \( Q \) by less than 15%. This result indicates that the change in \( N_t \) due to the polymer additive is very small in comparison to the dramatic reduction in the longitudinal velocity gradient. If this change in \( N_t \) can be neglected, we can estimate the change in \( \eta_{el} \) by noting the shift in the minima in Fig. 2. From these measurements the increase in elongational viscosity due to the polymer is seen to be roughly a factor of 5.

The polymer also alters the \( Y \)-dependence of the velocity field \( V(Y) \) shown in Fig. 3. This velocity profile is plotted at a point where the difference in behavior of the two solutions is clearly apparent, namely \( X/d = 1 \). The effects of the polymer weaken at positions downstream, as will be seen in data presented below. For the polymer-free vortex street, \( V(Y) \) is seen to have a minimum at a value of \( Y \) roughly equal to half a rod diameter (by symmetry this velocity component will go through a positive maximum at a negative value of \( Y \)). The fact that \( V(Y) \) is negative for \( Y > 0 \) and must be positive for \( Y < 0 \) establishes that the flow is converging to the center line, as expected. For the polymer-containing solution, \( V \approx 0 \) for an extended range of \( Y \) at this distance behind the rod. This indicates that the flow is not converging this close to the rod. These measurements are consistent with the data in Fig. 2, which show that the formation length of the vortices has been lengthened by the presence of the polymer.

We now move from the effect of the polymer on mean flow properties to its influence on the velocity fluctuations about the mean. Figure 4 shows the rms fluctuations in the transverse velocity component as a function of \( X \) measured at \( Y = 0 \). The vertical axis is

\[ u'(X)/U_f = \sqrt{\langle (u'_y(X,t)-\langle u'_y(X,t) \rangle)^2 \rangle}/U_f, \]

and the abscissa is \( \log(X/d) \). Here \( u'_y(X,t) \) is the time-
dependent transverse velocity component. Consider first the polymer-free measurements, designated as $v_0$. The maximum value of the function appears at a position $X$ called the formation length $l_d$. This length is comparable to that of the recirculation region present just below the onset of vortex shedding. The open circles in Fig. 4 show the corresponding quantity $v_{30}/U_f$ with the polymer present. The formation length is increased six-fold and the maximum value of $v$ is dramatically reduced.

In spite of the increase in $l_d$ produced by the polymer, it has little effect on the peak shedding frequency, as was previously observed, but there is a measurable downward shift. The polymer’s dramatic broadening of the frequency power spectrum $S(f)$ is seen in Fig. 5(a). These measurements were made at $X=3$ cm and with $U_f=200$ cm/s. The small downward shift of the peak frequency $f_s$ is a robust result, but its magnitude does vary with concentration, albeit weakly. This downward shift was previously reported by Usui et al. In an attempt to understand the origin of the broadening of $S(f)$ for the polymer-containing solution, measurements were made of the spread in time intervals $\delta t$ between successive zero crossings of $v_y(t)$. A histogram of the time intervals $\delta t$ displays a broad distribution, which demonstrates that the time between shedding events is not constant. In addition, the amplitude of $v_y(t)$ also fluctuates, as was seen in a time trace of this variable.

Whereas the spectral measurements were made using a PEO concentration of 30 wppm, spectra measured at concentrations as low as 14 wppm also showed a suppression of the peak in $S(f)$ and a broadening effect.

**IV. DISCUSSION**

The measurements in Figs. 2 and 4 show that the polymer has a significant effect on the boundary layer, increasing the formation length several fold. This increase is consistent with the presence of an elongational viscosity term in the Navier–Stokes equation. The stretching of the vortex formation region by the polymer additive is accompanied by a suppression of the transverse velocity fluctuations, as seen in Fig. 4. Since these fluctuations are instrumental in creating the vortex street, it is perhaps not surprising that an array of staggered vortices does not immediately appear downstream from the rod, as in Fig. 1(a), but develops only at a larger value of $X$, as seen in Fig. 1(b).

It remains to be understood how the polymer strongly broadens the power spectrum $S(f)$ of the velocity fluctuations below the rod. The origin of this broadening could simply be the randomization of the passage of identical pointlike vortices past the observation point, much like the randomness of a dripping faucet. On the other hand, its
source might be the temporal variation of the velocity amplitude. Both of these effects are present in our measurements of \( v_y(t) \).

The narrow width of \( \Delta f \) in the polymer-free soap solution [see Fig. 5(a), closed circles] establishes that the flow directly behind a rod is highly periodic. This periodicity is observed even within a diameter \( d \) of the rod, as seen in Fig. 5(b) (closed circles). The polymer additive strongly alters \( \Delta f \) near the rod, as is also seen in Fig. 5(b) (open circles). The height of the peak in \( \Delta f \) in Fig. 5(b) is four decades smaller than in the polymer-free measurements, demonstrating that the polymer suppresses the amplitude of the oscillations in \( v_y(t) \) and broadens the spectrum as well. At \( X/d = 1 \) there is hardly a remnant of a well-defined shedding frequency. It is clear from the spectra in Fig. 5 that the polymer additive does not destroy vortex shedding; it merely depresses it to a point further downstream. This observation is consistent with the measurements in Figs. 2 and 4, and the photographs in Fig. 1. Visual observation far below the rod reveals that the addition of the polymer does not significantly alter the ratio \( A \) of the lateral and longitudinal separation of the vortices. The measurements of \( A \) show it to be slightly lower than the Karman value of 0.28, but the uncertainty in this ratio is large, namely \( \pm 0.05 \).

V. SUMMARY

A small concentration of a polymer of high molecular weight is seen to strongly effect the creation and shedding of a Karman vortex street in a quasi-two-dimensional flowing soap film. The rms velocity fluctuations behind the rod are strongly suppressed by the polymer additive. Our principal finding is that at a low concentration of \( c = 30 \) ppm, the rms fluctuations in the velocity are suppressed at all downstream points. This finding implies that the polymer strongly reduces the magnitude of the velocity fluctuations caused by the presence of the rod. The experiments further suggest that the origin of this effect is the introduction of an elongational viscosity term in the Navier–Stokes equation.

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15. Dawn is a Proctor & Gamble product.