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NEAR WALL VISUAL MEASUREMENTS IN DRAG REDUCING FLOW

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ABSTRACT

A review of several explanations for the mechanisms of drag reduction is presented. Visual studies of ordinary liquids are reviewed briefly, and visual studies in drag reducing flow are discussed. Finally, current work at Ohio State University is described where high speed motion pictures will be taken of drag reducing flow using the technique of Brodkey and Corino.

INTRODUCTION

Drag reduction was first observed[1] in jellied gasolines during World War II, initiating many efforts to establish mechanisms. Drag reduction has been observed in several different experiments including pipeline flow and disks rotating in a fluid using high molecular weight polymers, association colloids such as soaps, and solid particles as additives. Effects of polymer additives have been widely studied, yet proposed theories are vague in explaining wall area alterations in turbulent flow.

Visual techniques, which eliminate probes or other foreign measuring devices in the flow, appear to offer the best prospects for elucidating the mechanism of how drag reducing additives alter the turbulent energy dissipation. This paper will review several of the proposed drag reduction theories, the visual techniques that are applicable to studying drag reduction, and the progress to date.

DRAG REDUCTION THEORIES PROPOSED IN LITERATURE

The earliest theory of drag reduction was by Oldroyd[43], who was aware of Toms' results[72]. Oldroyd proposed the existence of an abnormally mobile laminar sublayer, with a thickness of molecular dimensions. This sublayer gave slip at the wall. Oldroyd's theory still is not proven or disproven satisfactorily as discussed later on.

A review of the early literature up to June, 1965[28], found that most investigators favored viscoelastic effects as the cause of drag reduction[14,15], but offered no mechanism. Subsequently more specific suggestions have been advanced[3,22,28,31,49,60,62,63,67,74] as to how viscoelasticity might cause drag reduction. Savins[59] suggested that the molecular elastic elements of the macromolecules in solution store the kinetic energy of turbulent motion and then return the energy to the fluid so that energy is conserved when compared to the normal process of viscous dissipation into heat in the turbulent flow of a Newtonian liquid.

Astarita[3] suggested that the turbulence in viscoelastic fluids is less dissipative and offered some order of magnitude calculations in support. Shin[67] proposed three probable mechanisms: a restatement of Savin's hypothesis[59], anisotropic viscosity, and a solvent-sequestering ball theory similar to that of Hershey. Shin suggested that a knowledge of the actual molecular conformation in turbulent flow would enable one to decide which of the three mechanisms plays the most important role. Hershey and Zakin[28-31] suggested that the onset of drag reduction occurs when the relaxation time of the polymer molecule in solution equals a characteristic flow time for the tube in question at the point of incipient turbulent suppression (i.e., at a Deborah number[50] near unity). Elata, Lehrer, and Kahanovitz[17] and Ram, Finkelstein, and Elata[49] used a similar approach.

Virk et al.[73,74] hypothesized that the onset of drag reduction in the turbulent pipe flow of dilute polymer solutions occurs at a constant value of "a ratio of the dimensions of the macromolecule and the fine scale of the turbulent shear flow." Fabula et al.[22] had several suggestions, including that of Hershey and Zakin (formulated concurrently and independently, however) but most favored an explanation that the development of intense shear layers was modified by the action of clusters of macromolecules which may be formed by entanglement during flow. Other recent theories are by Tennekes[71], Squire, Castro, and Costrell[69], and Tanner[70].

Patterson and Zakin[45] showed by rough spectral calculations that the viscoelastic effect must be in the near-wall region and that viscoelasticity can give approximate predictions of drag reduction, using a Maxwell model for the fluid behavior. A comparison of their calculations with other proposed empirical functions and limitations is available[47].

All these hypotheses are necessarily vague as to just how the presence of a viscoelastic polymer molecule affects the boundary layer in turbulent flow and particularly the ejections of fluid elements, since these ejections can reasonably be expected to be responsible for the generation and maintenance of turbulence[8-11].

Savins[59] and Virk[74] indicated that a "slip velocity" effect could explain some of their results. But in suspension flow phenomena, Blair[7] and several others have shown that suspensions in turbulent flow tend to form a solute-free region near the wall. However, it has been proven conclusively by Wells and Spangler[79] and by Davies and Ponter[12] that the mechanism for drag reduction requires polymer in the wall area only, and the concentration in the center portion of the flow makes little difference.

Although an "effective slip velocity" from solute migration can be ruled out, a slip velocity related to other mechanisms could be present. A sure way to discover whether or not there is a slip velocity is to examine the velocity profiles in drag reducing solutions. This has been attempted by many investigators, the first of whom was Shaver[65,66]. Hershey[28] carefully recalculated all of the data[52,65,77] available up to June, 1965, and showed that no conclusions on wall effects could be made.

In the best data at that time, the average velocity calculated by a mass balance from integrating the velocity readings V(r) from pressure-sensitive probes over the area of the tube:

$$\bar{v} = \int_0^{2\pi} \int_0^{R} V(r)\, dr\, d\theta \qquad (1)$$

was systematically in error with the average velocity $\bar{v}$ measured independently. Although some investigators[17,19,40,46] were able to eliminate this problem, Astarita and Nicodema[4] showed that in a viscoelastic turbulent stream, Pitot tube readings were made up of a first normal stress contribution, an integral normal stress contribution, and a kinetic contribution. All these contributions are of comparable orders of magnitude, and the conclusion then was that measurements made with ordinary Pitot tube scanning experiments are generally not reliable for determing velocity profiles in viscoelastic flows[4].

Metzner and Astarita[39] analyzed the flow of viscoelastic materials around any probe (e.g., Pitot, hot-wire, hot-film) inserted in a turbulent field. They concluded that in light of the restrictions on the flow at high Deborah number[37,38,50], the boundary layer is thickened appreciably and the readings from the probes cannot be interpreted without further analysis. The significance of this analysis is to question the results from the earlier investigations that have used hot-film probes and uncalibrated Pitot tubes. Their analysis posed a possible explanation to account for apparent abnormalities such as intensity of turbulence measurements that are actually higher in drag reducing solutions than in Newtonian liquids, as found by Patterson [44] and Rodriguez[53] in turbulent flow. Also the recent data of Rudd[57] indicated high intensities near the wall in drag reducing flows. Rudd used a laser technique which eliminates any error from introducing a probe into the flow. Furthermore, it is possible to calibrate the hot-film probe directly in the viscoelastic material.[54] The properly calibrated hot-film probe also indicated high turbulence intensity values. A reinterpretation[55] of the Metzner-Astarita analysis[39] implied that it is possible for the observed intensities to be either low or high depending on probe geometry.

Other anomalities also exist, as mentioned by Smith et al.[68] However, a more recent study[55] showed that the hot-film cylinder used by Smith, et al.[68] may have experienced eddy shedding which would cause anomalous results. Wedge film probes do not have this problem.[44,53,55]

Nicodemo, et al.[42] measured velocity profiles in drag reducing flow using a Pitot tube calibrated by towing. Their profiles were integrated yielding the correct mean velocity. Some profiles seemed to show a sharp break about halfway between the wall and the centerline. However, it appears that their profiles are not substantially different from profiles in ordinary fluids such as water. Seyer[64] has confirmed these results by his photographs, to be discussed later.

The two most recent velocity profile measurements[42,64] just described seem to cast doubts on the slip velocity theory mentioned earlier. Reusswig and Ling offer yet another experimental refutation of the slip velocity theory.[51]

Many investigators have associated thickening of the viscous sublayer with drag reduction.[16,17,18,20,33,40,46,57,66] The claim of a pronounced thickening of the viscous sublayer (not to be confused with the developing boundary layer!) is based on the fact that on a u^+ versus y^+ plot, the linear region extends to a higher y^+ in the drag reducing flow as compared to the solvent. Nicodemo et al.[40] claim their profiles rule out interpretations of drag reduction based on the idea of a thicker sublayer.

In view of the difficulties in velocity profile measurement, it is difficult to draw a firm conclusion regarding the wall region velocity profile in drag reducing fluids. Hopefully the visual study to be discussed later will be able to further clarify the profile in the near wall region.

The effect of elongational viscosity in turbulent drag reduction flow has been widely discussed.[5,6,61] The elongational viscosity (μ_e) is defined as the longitudinal stress divided by the rate of elongation:

$$\frac{\tau_{11}}{\Gamma} = \mu_e = \frac{4\mu}{1 - (2\ \theta\ \Gamma)^2} \qquad (2)$$

where μ is the ordinary steady shear viscosity, θ the relaxation time of the fluid, and Γ the rate of elongation. In Eq. 2 the quantity $(2\ \theta\ \Gamma)^2$ must be bounded:

$$0 \leq (2\ \theta\ \Gamma)^2 \leq 1 \qquad (3)$$

in order for μ_e to be always positive. At low rates of elongation, $\mu_e \approx 4\mu$, while at high rates, μ_e may increase without limit. If the assumption is made that the stresses sustaining elongational deformations are similar in Newtonian and drag reducing systems, then the rate of elongation, Γ, must be lower during drag reduction than in ordinary flow.[64]

A molecular dumbell model was used by Gordon[25] to propose a simple mechanistic picture of drag reduction as observed experimentally by other workers. Everage and Gordon[21] also reworked the Denn-Marrucci analysis[13] for a more realistic constitutive equation to show that there should not be a limiting stretching rate for a viscoelastic fluid until the stress exceeds at least an order of magnitude above the Newtonian value.

Another theory of drag reduction is the additive adsorption theory. This theory, as explained by Arunachalam and Fulford,[2] is based on the assumption of adsorption of part of the polymer molecule onto the pipe walls. The remainder of the polymer molecule remains in the flow and protrudes from the surface into the solution. Thus the nature of a flow near such a wall might be altered and drag reduction caused. The effect of polymer adsorption in polyox systems has been studied extensively by Peyser, et al.[48] Their conclusion was that adsorption effects are unimportant compared to other drag reduction mechanisms.

Ruckenstein's analysis[56] used a renewal model to describe wall turbulence and a Maxwell model as a constitutive equation. He identified the characteristic flow time, introduced previously,[29,31] with the contact time a fluid element has with the wall. His calculation showed that the time-average wall shear stress must be lower for the Maxwell fluid than for a Newtonian fluid. Other treatments of drag reduction using a surface renewal model are by Hansen[27] and Meek and Baer.[34]

In summary, most theories agree that the drag reducing additive imparts elastic properties to the viscous liquid. How the viscoelastic flow differs from the ordinary liquid flow is presently unclear. Two of the more credible explanations of the drag reduction phenomena are: 1) a slip velocity effect at the wall and 2) an anisotropic viscosity, especially a large elongational viscosity in the flow direction.

VISUAL MEASUREMENTS IN TURBULENT FLOW

1. - Pure Liquids

The earliest visual studies were made by Fage and Townend[23] and Fage[24] who used an ultramicroscope to examine fluid motion near the wall in pipe flow. The flow was marked with dust naturally present. They showed that turbulent eddies penetrated into the $0 \leq y^+ \leq 4$ region.

Nedderman[41] used a technique of still photography, marking the flow with small air bubbles.

The most recent and most informative visual studies were those of Kline and coworkers[32,58,60] and Brodkey and coworkers.[8,10] Both studies were completed in 1965.[10] Kline and coworkers studied the turbulent boundary layer over a flat plate using both a dye injection and a hydrogen bubble technique for marking the flow. Brodkey and coworkers performed experiments in pipe flow, using a suspension of magnesium oxide in trichloroethylene. These two techniques have yielded a much clearer picture of the events occurring in the wall region in turbulent flow.

2. - Drag Reducing Fluids

Both Shaver[65] and Meter[35,36] injected dye into a transparent pipe under conditions of drag reduction. They reported less turbulence intensity in the drag reducing solution than in the pure solvent. However, their comparisons were at the same flow rates. Flow at the same Reynolds numbers would have provided more insight into the mechanism of drag reduction.

Seyer and Metzner[62,63] used as tracers air bubbles suspended in an ET-597 polyacrylamide-water solution to get still photographs in drag reducing flow.

The bubbles were illuminated with a carbon arc lamp whose beam was periodically interrupted using a high speed slotted wheel. Their field of view was about 1.5 inches using a magnification of 3.5X. The instantaneous axial and radial velocity components were calculated by measuring the axial and radial components of the length of streaks on the still photograph. Time-averaged axial velocities and axial and radial intensities were then computed from the measurements.

Seyer and Metzner's interpretation of their photographs was that for concentrated solutions exhibiting drag reduction at all turbulent Reynolds numbers, the flow may be transitional near Reynolds numbers of 10^5. The velocity profile for drag reduction was flatter than non-drag reducing solutions in the turbulent core, similar to Virk's hot film measurements.[74] The transitional nature of drag reducing flow was not confirmed by Hanratty.[26]

A research project under the direction of Professor William Tiederman at Oklahoma State University is a visual study of drag reducing flow over a flat plate using the technique of Kline, et al.[32] Preliminary analysis of their study (not quite finished on October 4, 1971) agrees with most of the conclusions of Hanratty,[26] which were that in drag reducing flow there is a decrease in the quantity and intensity of low speed fluid motions and that there was no transitional-type intermittency.

3. - Proposed Visual Measurements

The experimental technique of Corino and Brodkey[9,11] will be used. Solid MgO particles of colloidal size are suspended in trichloroethylene and their motions near the glass pipe wall photographed with a high speed movie camera both stationary and moving with the flow. The glass pipe is submerged in trichloroethylene thus eliminating problems of refraction since the fluid has a refractive index of 1.474 and the glass pipe 1.473 - 1.477. This technique requires no injection, no measuring device in the flow and is essentially a one-phase flow.

Visual studies using the Corino-Brodkey technique are more difficult in drag reducing flow than in pure trichloroethylene, primarily because of the critical Reynolds number effect.[28,29,31,73,74,75] Visual studies are most effective at low flow rates where turbulent events occur less frequently. However, the critical stress for the onset of drag reduction requires that if drag reduction begins at a Reynolds number of 25,000 in a 1/2-inch pipe, the critical Reynolds number will be about 50,000 in a 1-inch pipe, and 100,000 in a 2-inch pipe.

Corino's photographs[10] were made at a Reynolds number of 20,000 in a 2-inch pipe. He took a few rolls of film at 50,000, but no analysis was attempted. The critical Reynolds number for the most effective polymer additives in trichloroethylene is apparently between 150,000 and 200,000 for a 2-inch pipe. Thus a 1-inch pipe will be required as well as improvements in Corino's original technique (see Appendix).

Both polymer and soap additives will be tried. We plan to examine the regions above, at, and below the critical Reynolds number where drag reduction begins. Also the flow pattern around a Pitot tube and around a hot-film probe will be examined in order to clarify how the presence of a drag reducing additive affects the flow pattern in the neighborhood of typical probes.

The flow visualization technique should help decide among the various theories of drag reduction. The presence or absence of slip velocity, intermittency, and thickened boundary layer as discussed earlier should be decided clearly by analysis of the movies. Further information to be obtained includes intensity of turbulence (qualitative), frequency of ejection, scale of ejection, location of ejection in relation to the wall, and wall region velocity profiles.

APPENDIX

Mr. Charles N. Carpenter, Ph.D. candidate in the department of Chemical Engineering, has made a number of improvements since Corino's work:

A Higher Light Intensity. A 500 watt mercury lamp will replace the 100 watt mercury lamp giving more than three times the previous light intensity. The mercury lamp gives better recording resolution at its shorter wave lengths and is safer to use than say a Xenon lamp.

Light Condensing System. A light condenser adapted to accept filters and heat absorbing glass was added to gather and refocus a narrow beam of light through the pipe wall region of interest. This replaces the slit technique used by Corino to get a black background and uses the light more efficiently.

Camera Lens Adaptor. A camera lens adaptor was made to hold the reversed lens more securely. It includes a lens shade and a light trap to reduce extension tube reflections.

Higher Speed Film. A higher speed photographic film (Kodak 2485, ASA 8000) was found with a film sensitivity four times that previously used (Kodak 2475, ASA 2000).

Both the higher intensity light and higher speed film allow options of reducing an f/2.0 lens aperture to a more optimum resolving aperture and use of selective filters such as neutral density, restricted wave length, or polaroid for better recording effects.

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DISCUSSION

G. L. DONAHUE (Oklahoma State University): Again, talking about the bursting pictures that we've done in polymer solutions, we're using a fairly large channel. It has a hydraulic diameter of about 3 inches. We found that by using polyethylene oxide (FRA) in water we can get critical wall shears that will give us friction reduction at a Reynolds number of 17,000 and a wall shear stress of about one dyne per square centimeter. This is approximately the same wall shear rates that they are using at Stanford and it is very easy to photograph.

HERSHEY: In organic fluids which we have to use to match the index of refraction, the drag reducing effect is not as pronounced as it is in aqueous fluids. The additives are not as effective and higher velocities are required for drag reduction.

DONAHUE: What specifically are you going to look for?

HERSHEY: Well, we are going to look for just how this ejection event is modified. There are a lot of calculations that can be made once you have these pictures. You can calculate the shear rates, the angle of ejection and so on. If we are successful in taking these pictures it will help us to try to pick among the various theories I have discussed.

DONAHUE: We already have ejection trajectories and those sort of things. We use a laser velocimeter to measure the velocity profile and we're getting wall shear from the slope of the velocity profile at the wall. Also we're running two different diameter pipes in parallel with our channel and we measure the drag reduction as a function of wall shear in the pipes. We see no diameter effect with our particular flow if percent friction reduction is plotted against wall shear.

W. G. TIEDERMAN (Oklahoma State University): One of the problems we encountered in trying to do flow visualization and friction reduction at the same time was that the two events run counter to each other. As you go up in wall shear, your streak spacing is going to decrease rather markedly. The critical feature for flow visualization is being able to optically resolve the streaks. And that is limited to some extent by the rate at which dye or whatever you're going to use to mark the streaks diffuses. For that reason, we made the choice of going to a lower critical shear stress rather than to higher flow velocities.

HERSHEY: That is a problem with our technique, too.

S. KLINE (Stanford University): It is critical in any visualization experiment to get the frequencies low enough and the sizes big enough. That was why we went to water systems in the first place.