A Note on the Mechanism of Drag Reduction

There is experimental evidence that the region near the wall plays the main role in drag reduction occurring in turbulent pipe flow of very dilute solutions of macromolecules. Indeed, Wells and Spangler[1] have observed an essentially instantaneous drag reduction when the drag-reducing additive was introduced near the wall and a delay in drag until macromolecules introduced at the center diffused to the wall. Further, Fabula[2] has observed no influence of the drag-reducing agents on turbulent spectrum in homogeneous grid turbulence. The drag reduction was attributed to the viscoelastic behavior of these solutions near the wall.

In previous papers,[3,4] physical models for the wall turbulence were used to explain the manner in which viscoelasticity causes drag reduction. Turbulence near the wall was represented by a succession along the wall of developing and decaying boundary layers. Because of turbulent fluctuations, elements of liquid approach the wall up to a certain distance, move along the wall in short paths (stochastically distributed), and, becoming unstable, dissolve in the bulk of the liquid, being replaced by other elements. The bursting process observed for turbulent flow in the region near the wall by Kline et al.[5] and by Corino and Brodkey[6] gives support to this model.

The drag reduction is due to two effects of viscoelasticity: (1) Using a Maxwell model as a constitutive equation for a viscoelastic fluid, one can show that the instantaneous shear stress at the wall is smaller in the viscoelastic fluid than in the corresponding Newtonian fluid. If a constitutive equation containing, besides the relaxation time, the retardation time is applied, then the effect is less important. If the ratio of the times is unity, the fluid behaves as a Newtonian fluid. (2) The replacement (renewal) of the elements of liquid following short paths along the wall takes place as a result of turbulent fluctuations. In order to be replaced by other elements, the element moving along the wall must first relax its elastic stresses because only in this manner will the viscous deformations needed for its replacement occur. This fact introduces a delay in the replacement process compared to a Newtonian fluid. Because the instantaneous shear stress at the wall decreases for larger contact times with the wall, the average shear stress at the wall (defined over the time of contact with the wall) decreases.

The effect of viscoelasticity on replacement can be explained with a different picture. The replacement is caused by the bursting process (taking place near the wall) which is of a stretching nature.[6] An elongational flow might consequently be a reasonable simplified representation of the "dissolution" of the elements of liquid after their contact with the wall. Lumley[7] estimated that the elongational viscosity of a viscoelastic fluid may be much greater than the shear viscosity. The problem of elongational viscosity was reviewed and discussed recently by Ting[8] who concluded that the elongational viscosity of a viscoelastic liquid is, under certain conditions, very large. Such a large elongational viscosity delays the replacement (renewal) compared to a Newtonian fluid. As concerns the effect of the retardation time, one may observe that if the ratio between the retardation and relaxation time is of about 0.7 as claimed by Ting, the effect of viscoelasticity on the shear flow is negligible, but remains important on the elongational flow.[8] If one accepts a large value for this ratio, then only the second effect, discussed under (2), is important.

Ting,[8] discussing our model, has presented only one of the effects, that discussed above under (1), and has ignored the second effect, discussed above under (2). He also chose to relate drag reduction to the high elongational viscosity. It is shown above that this representation is related to the effect discussed under (2), being an alternative explanation of the same effect.

References

1. C. S. Well and J. G. Spangler, Ling-Temco-Vought Research Center, Report No. 0-71000/TR-4, 1967.
2. A. G. Fabula, Report to U.S. Bureau of Naval Weapons, Pennsylvania State Univ., 1966.
3. E. Ruckenstein, *Chem. Eng. Sci.*, **26**, 1075 (1971); *ibid.*, **27**, 947 (1972).
4. E. Ruckenstein, *Chem. Eng. J.*, **4**, 180 (1972).
5. S. J. Kline, H. T. Kim, and W. C. Reynolds, *J. Fluid Mech.*, **50**, 133 (1971).
6. E. R. Corino and R. S. Brodkey, *J. Fluid Mech.*, **37**, 1 (1969).
7. J. L. Lumley, *Ann. Rev. Fluid Mech.* **1**, 367 (1969).
8. R. Y. Ting, *J. Appl. Polym. Sci.*, **16**, 3169 (1972).

E. RUCKENSTEIN

Department of Chemical Engineering
University of Delaware
Newark, Delaware 19711

Received March 27, 1973