Anisotropy of Viscosity of Drag Reducing Solution

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Drag reduction in turbulent flow in a pipe can be achieved by the addition of small amounts of surfactants or polymers to water. It was shown (Zakin et al., 1996) that the magnitude of the effect with surfactants can be even greater than with polymers. The interference of long micelles with velocity fluctuations and their influence on the transport of turbulent eddies, as discussed by Myska et al. (1997), might be considered as a good explanation of the phenomenon. However, a more sophisticated interpretation with the use of particular viscous properties is also possible. Drag reduction can be viewed as a consequence of anisotropy of the viscosity of the surfactant solution. This anisotropy originates in the viscous sublayer and the transition layer. The micelles are deformed, stretched out, and aligned with the flow direction, and, therefore, there are different resistances to mixing in different directions and against the development and movement of turbulent vortices. The largest resistance against pulsating motion is in the direction perpendicular to the flow. Both the frequency and amplitude of fluctuations are much smaller in the drag reducing liquid than in water at the same Reynolds number, and the turbulence generation is reduced (Myska et al., 1997).

A classic experiment conducted to determine the dynamic viscosities in the flow direction and in the perpendicular direction was described by Malkin et al. (1979). They measured the settling velocity of a sphere in the velocity field of a surfactant in the gap of a Couette viscometer. Viscosity in the flow direction was measured by the viscometer and the perpendicular viscosity was calculated from the Stokes equation. They found the maximum ratio of the two to be 1.7, with the kinematic viscosity of the surfactant in the flow direction $\nu_{s,z}$ much smaller than the kinematic surfactant viscosity in the radial direction $\nu_{s,r}$. The coefficient of the local viscous anisotropy may thus be defined as

$$K_a = \frac{\nu_{s,r}}{\nu_{s,z}} \tag{1}$$

and it can be related to the general hydrodynamic conditions in the pipe via pressure. It is evident that the coefficient of the anisotropy of the viscosity changes along the radius of the tube; Povkh et al. (1979) show the relation between the mean coefficient of anisotropy and pressure in turbulent flow in a tube to be

$$\overline{K}_a^2 = \frac{i_w}{i_s} \tag{2}$$

where i_s and i_w are pressure drops in surfactant solution and water, respectively, and $\overline{K}_a$ is the mean value of the coefficient. Because of the negligible difference in density of water and dilute surfactant solution, Eq. 1 applies for dynamic viscosities as well. From Eq. 2, the calculation using pressure drop vs. bulk velocity data published by Myska et al. (1996) yields increasing values of $\overline{K}_a$ with increase in the bulk velocity. They rise from $\overline{K}_a = 1.9$ at 0.8 m/s up to approximately 3 at 3.4 m/s for the surfactant Habon G whose effectiveness is greater than that for polymers. These pressure drop values were obtained in a 39.4-mm tube both for water and surfactant solution.

It is possible to calculate in this way the coefficient of anisotropy, which is pertinent to the maximum drag reduction asymptote in surfactants. An equation presented by Povkh et al. (1979) can be used for this purpose. Plots of f-Re in the drag reduction literature are usually constructed using the water viscosity ν_w and not the surfactant viscosity. Thus, values of the friction coefficient f, both in water and in surfactant solution at the same Reynolds number, are in fact valid also at the same bulk velocity if taken in the same tube.

The equation derived by Povkh et al. (1979) is easy to transcribe into the form

$$\frac{f_w - f_s}{f_w} = 1 - \frac{\dfrac{16}{Re} + \left(\dfrac{0.0791}{Re^{0.25}} - \dfrac{16}{Re}\right)\dfrac{1}{\overline{K}_a^2}}{\dfrac{0.0791}{Re^{0.25}}} \tag{3}$$

and values $\overline{K}_a$ can be calculated from f_w and f_s vs. Reynolds number data. From the maximum drag reduction asymptote for surfactants (Zakin et al., 1996, and Myska et al., 1997), we have found constant $\overline{K}_a \cong 3.15$ throughout Reynolds number range from 10,000 to 150,000. This is obviously the maximum possible value of the mean coefficient of anisotropy. The same calculation obtained for polymers using the Virk asymptote (Virk et al., 1970) shows increasing values of the coefficient with increase in Re. It yields a value of $\overline{K}_a$ approximately 2.6 at $Re = 100{,}000$.

The anisotropy of the viscosity in drag reducing surfactants is thus much greater than expected earlier when the value 2 was considered and discussed as optimum (Povkh et al., 1979) and also larger than the value 1.7 obtained by experiments in a surfactant (Malkin et al., 1979). These values are not consistent with values obtained from data with drag reduction approaching the maximum drag reduction asymptote limit.

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