New Limiting Drag Reduction and Velocity Profile Asymptotes for Nonpolymeric Additives Systems

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Reduction of friction losses in turbulent flows caused by the presence of low concentrations of aluminum disoap and high polymer additives was first reported about fifty years ago (Mysels, 1949; Toms, 1948). Since then there have been a large number of studies of drag reduction, most of which used high polymers, and several excellent reviews exist (Patterson et al., 1969; Hoyt, 1972; Virk, 1975; Sellin, et al. 1982a,b; Hoyt, 1986; Shenoy, 1984). High polymer additives have found important niche applications in crude oil and petroleum product transport (Burger et al., 1982; Motier et al., 1984), in fire fighting (Union Carbide, 1966), in increasing sewer flows (Sellin, 1977) and in jet cutting (Summers and Zakin, 1975), Virk et al. (1970, 1971) proposed equations for a limiting maximum drag reduction asymptote for high polymers and also for an elastic sublayer velocity profile limit. We show here from our experimental data and from those of a number of other investigators (Fankhänel, 1991; Weber, 1990; Althaus, 1991; Ohlendorf and Schwarz, 1984; Pollert et al., 1993; Myska and Vlasak, 1988; Sylvester and Smith, 1979; Myska and Vocel, 1977; McMillan et al., 1971) that both limits proposed by Virk are not valid for aqueous surfactant and aluminum disoap in hydrocarbon systems. New limiting equations for them are proposed. These different behaviors suggest that the mechanism for high polymer drag reduction is probably different than that for micellar systems.

Polymer effectiveness is dependent on the presence of high molecular weight species which limits their applications because of the susceptibility of high molecular weight components to degradation in high shear flows or extensional flows. The former are encountered when passing through pumps and the latter in expansion or contraction flows. Thus, high polymer additives are limited to once-through flows and are not suited for recirculation systems.

In the past decade, considerable interest has developed in nondegrading or "repairable" drag reducing additives for use in district heating and cooling systems to lower the pumping energy requirements (Rose et al., 1984; Pollert et al., 1994). In district heating systems, cogeneration or waste heat sources are used to heat water in a primary loop which circulates the hot water to heat-exchange stations. The heat exchanged to secondary loops provides hot water to heat nearby buildings or to heat hot water for household use. They are widely used in northern and eastern Europe, and their use in the U.S., Canada, Japan, and Korea is expanding. District heating systems conserve energy because of their use of waste heat and centralized production and distribution of heat, and their elimination of often inefficient burners in individual buildings. Thus, they reduce the amount of fossil fuel burned. District cooling systems operate in a similar manner.

Most promising are cationic surfactants of the quaternary ammonium type with appropriate organic counterions. Under the right conditions of surfactant/counterion chemical structures, ratios, concentrations and temperature, they form rodlike micelles. The resulting microstructure imparts viscoelasticity to the solution. The microstructure is mechanically degraded when passing through a high shear pump such as a centrifugal pump, but the structures reform quickly no matter how many times they are broken up by shear. Though surfactant drag reducing additives require higher concentrations than high polymers, their long life and greater potential percent reduction in energy loss make them very attractive for recirculation flows.

Virk et al. (1970, 1971) examined friction factor and velocity profile results for a large number of high polymer solutions, mostly but not all, in water. They noted that at relatively low concentrations many solutions reached lower limiting values in their frictions factor—Reynolds number data. Virk et al. (1970) proposed an equation for the limiting maximum drag reduction asymptote (MDRA). The limiting equation is independent of polymer species, molecular weight, and concentration. The equation, often referred to as the Virk MDRA is

$$\frac{1}{\sqrt{f}} = 19\log\left(N_{Re}\sqrt{f}\right) - 32.4 \qquad (1)$$

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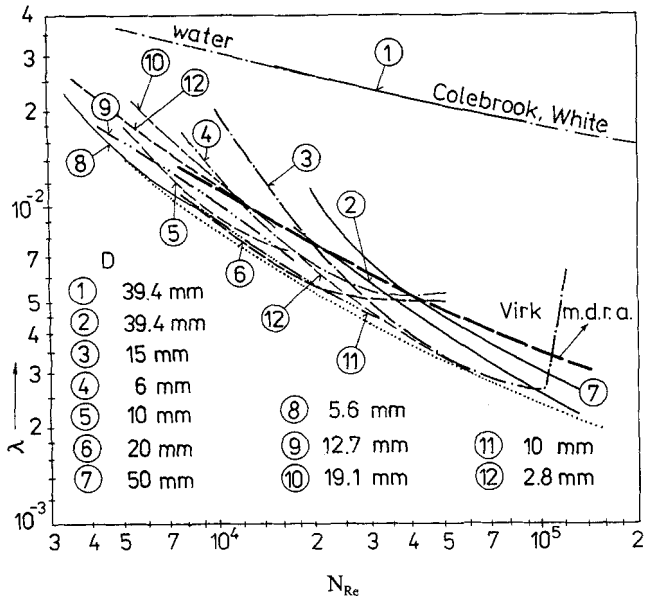

Figure 1. f vs. *Re*.

(1) Our data for water; (2) our data for Habon G, Ethoquad T/13/50 (tallow tris-hydroxyethyl ammonium acetate) with sodium salicylate (1.45 mM/3.9 mM) and Arquad 18/50 (octadecyl trimethyl ammonium acetate) with sodium salicylate (1.6 mM/4 mM) in water; (3) data of Fankhänel (1991), Weber (1990), and Althaus (1991) for Habon G, Dobon G and Obon G ($C_{16}H_{33}$, $C_{18}H_{37}$ and $C_{22}H_{45}$ dimethyl hydroxyethyl ammonium-3 hydroxy-2 naphthoate) in water; (4) data of Ohlendorf and Schwarz (1984) for Habon (hexadecyl trimethyl ammonium-3-hydroxy-2 naphthoate) (1,000 ppm) in water; (5) (6) data of Pollert, et al (1993) for Habon G (2 mM) in water; (7) data of Myska and Vlasak (1988) for SEAN (a 1.2 g/L mixture of Carboxy pentadecyl trimethylammonium bromide, commercial septonex and α-naphthol) in water; (8) (9) (10) data of Sylvester and Smith (1979) for aluminum dialkyl phosphate (300 ppm) in kerosene; (11) data of Myska and Vocel (1977) for SEAN (1.55 g/L) in water; (12) data of McMillan et al. (1971) for aluminum distearate (6,000 ppm) in toluene; .....-limiting drag reduction curve for surfactants and aluminum disoaps.

or

$$f \cong 0.58\ N_{Re}^{-0.58}\ (N_{Re}\ 4{,}000 - 40{,}000) \qquad (2)$$

where f is the Fanning friction factor and N_{Re} is the Reynolds number. A number of investigators using surfactant drag reducing additives and aluminum disoaps have observed friction factors which lie below the Virk MDRA. Data for 1,000 ppm Habon G (hexadecyl dimethyl hydroxyethyl ammonium-2-hydroxy-3-naphthoate), for several other dilute aqueous surfactant solutions, and for two aluminum disoap additives in hydrocarbon solvents are shown in Figure 1. In each of these systems, friction factor data significantly below the Virk MDRA are observed. A limiting curve which envelopes these data is shown in Figure 1. Its equation is

$$\lambda = 4f = 1.26\ N_{Re}^{-0.55} \qquad (3)$$

where the Colebrook White friction factor $\lambda = 4f$.

Virk also noted that the mean velocity profile in turbulent pipe flow underwent changes as concentration of polymer increased. An extended steep elastic sublayer region developed outside the viscous wall region ($y^+ (\geq 11.6)$. Still further from the wall, a core region profile extended parallel to the Newtonian solvent core profile to the center of the pipe. Eventually, at high concentration, the steep region prevails across the entire core (see Virk elastic sublayer in Figure 2): The equation for the elastic sublayer asymptotic velocity profile region for high polymer drag reducing systems is

$$u+ = 26.9 \log_{10} y^+ - 17 \qquad (4)$$

where u^+ is mean local velocity divided by friction velocity and y^+ is dimensionless distance from the wall. This steep region across the entire profile is associated with the MDRA (Eqs. 1 and 2).

Shown on Figure 2, along with Virk's mean velocity profile asymptote, are u^+ vs. y^+ data we have obtained for a 500 ppm solution of Habon G at several Reynolds numbers. The velocity profile data away from the wall ($y^+ > 15$) are much steeper than the high polymer asymptote. At high values of y^+, which increase with Reynolds number, the profiles bend over and the core region is horizontal. Similar results are obtained with 1,000 ppm Habon G solutions. The limiting equation for the elastic sublayer profile for those data is

$$u^+ = 53.9 \log_{10} y^+ - 65 \qquad (5)$$

The steep velocity profiles of the surfactant solutions are accompanied by friction factors which lie below the MDRA. They indicate a mixing length constant of about 0.02, even smaller than the 0.04 of Eq. 5. Drag reducing surfactant sys-

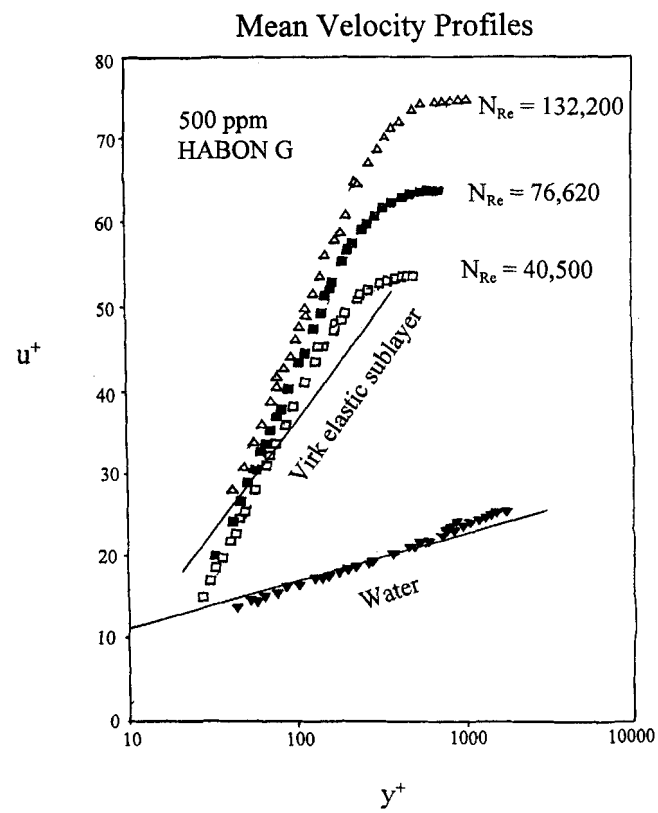

Figure 2. Mean velocity profiles.

tem velocity profiles steeper than that predicted by Eq. 5 have also been observed by Bewersdorff and Ohlendorf (1988) and Bewersdorff and Thiel (1993), so 53.9 may not be the ultimate slope.

Thus, there are significant differences in limiting friction factors and velocity profiles between high polymer drag reducing solutions and surfactant and aluminum disoap solutions. This strongly suggests that the mechanisms for drag reduction are different for high polymers and for surfactants and soaps. The reasons for this are not clear, but may be due to network structures formed under mild shear by the rod-shaped micelles in these systems. Cryo-TEM micrographs of cationic surfactant/counterion surfactant systems similar to some of those shown in Figure 1 show tight networks of branched and connected thread-like micelles (for example, See Figure 1, Magid et al., 1990). These have been called shear-induced-structures in which tangled networks of long micellar worms are formed. The network structure must be more effective than even MDRA polymer solutions in reducing turbulence production and turbulent eddy generation.

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