

SHORT COMMUNICATION

The Drag Reduction by Ultrahigh-Molecular-Weight Polystyrene

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The reduction of turbulent drag brought about by dissolution of a small amount of a polymer into a fluid is known as drag reduction phenomenon.¹ Studies on this phenomenon have shown that the Reynolds number at the onset of drag reduction is influenced by flow geometry,² polymer species, polymer concentration,³ and polymer molecular weight.⁴

Our previous study⁵ was concerned with the drag reduction of polyelectrolyte solutions measured by a rolling ball viscometer.⁵ The present study was undertaken to investigate drag reduction due to ultrahigh-molecular-weight polystyrene in benzene, with a view to obtaining information on the influence of flow geometry, polymer concentration, and temperature on the Reynolds number at the onset of drag reduction.

EXPERIMENTAL

Drag reduction was studied using an apparatus consisting of an inclined tube and a rolling ball, which is essentially an instrument for viscosity measurement at high temperatures and pressures.⁶ A general study with this apparatus of laminar and laminar-turbulent flow was reported by Hubbud and Brown.⁷

According to Hubbud and Brown, the drag coefficient C_D and the Reynolds number Re are defined by

$$C_D = \frac{f}{l^2 \rho u^2} \quad (1)$$

$$Re = \frac{lu\rho}{\eta} \quad (2)$$

where l is the characteristic length of the flow field and defined by the equivalent diameter usually employed in hydraulics for non-circular channels. This diameter is equal to four times the cross-sectional area of the tube divided by the perimeter. The equivalent diameter l of the crescent-shaped space in the present apparatus is defined by

$$l = 4 \frac{\pi(D^2 - d^2)}{4\pi(D + d)} = D - d \quad (3)$$

where D is the tube diameter and d , the ball diameter. Since, according to the above-mentioned definition, the characteristic length of a pipe flow is equal to the pipe diameter, the Reynolds number in eq 2 may be compared with the Reynolds number defined in terms of the pipe diameter in the pipe flow. u is the average fluid velocity which is related to the ball velocity V by the equation

$$\frac{u}{V} = \frac{d^2}{D^2 - d^2} \quad (4)$$

In the above equations, ρ is the density of the fluid, η , the viscosity of the fluid, and f , the force driving the ball represented by

$$f = \frac{5}{7} \cdot \frac{1}{6} d^3 (\rho_s - \rho) g \sin \theta \quad (5)$$

where the coefficient $5/7$ is the fractional gravity that causes the translational motion of the rolling ball, ρ_s , the density of the ball, and θ , the angle between the tube and the horizontal plane.

The drag reduction phenomenon was observed in the turbulent flow region by measuring the falling velocity of the rolling ball at various θ .⁵ The diameter of the glass tube was 1.57₈ cm and those of

the four steel balls used were 1.2, 1.3, 1.4, and 1.5 cm. The value of 7.856 g cm^{-3} at 25°C was used for the density of the steel balls.

The polymer sample used in the present investigation was an unfractionated ultrahigh-molecular-weight polystyrene, a commercial product IK-1500 of the Japan Synthetic Rubber Co. (JSR). Its molecular weight was 4.8×10^7 . The sample was purified by washing with methanol. Benzene was used as the solvent, and the polymer concentration ranged from 11.6 to 93.1 ppm (by weight). The viscosity of the solutions was measured using a Ubbelohde viscometer. No effects of shear degradation on the rheological properties were observed in the present study. For example, the terminal velocity of the 1.2 cm ball in 93.1 ppm solutions was reproducible within *ca.* 0.25% at $\sin \theta = 0.861$.

RESULTS AND DISCUSSION

The falling velocity of the ball V for simple liquids (benzene, water, water-glycerol) and a 93.1 ppm polymer solution was measured over the range of θ from 12° to 75° at 25°C , using the balls mentioned above. The drag coefficient C_D and the Reynolds number Re were calculated respectively from eq 1 and eq 2, with the density and viscosity of benzene at 25°C taken to be 0.874 g cm^{-3} and 0.602 m Pa s , respectively. The density of the solution assumed to be that of benzene, and the relative viscosity is shown in Table I.

The variation of $\log C_D$ with $\log Re$ is shown in Figure 1. The values of $\log C_D$ for benzene decrease with increasing Re and show breaks at high Reynolds numbers for the 1.2, 1.3, and 1.4 cm balls (see dotted lines). This behavior was also noted in the $\log C_D$ vs. $\log Re$ plot for the 93.1 ppm solution. The value of Re at the break point for benzene with the 1.2 cm ball corresponds to a θ of *ca.* 70° . Above this angle, the motion of the ball became visibly irregular and the slip of the ball was observed.

Effect of Equivalent Diameter on Drag Reduction

By dimensional analysis, the following relationship was obtained by Hubbard and Brown⁷:

$$\frac{f}{l^2 \rho u^2} = F\left(\frac{l u \rho}{\eta}\right) \quad (6)$$

The form of the function F is complicated, but may

Table I. Reynolds numbers at the onset of drag reduction for IK-1500 solutions in benzene; the equivalent diameter of the tube was 0.378 cm

Temperature	Concentration	Relative viscosity	Reynolds number
$^\circ\text{C}$	ppm		
25	11.6	1.008	1900
25	23.3	1.024	1680
25	46.6	1.077	1470
25	93.1	1.151	1120
45	46.6	1.075	1920
6	46.6	1.098	1120

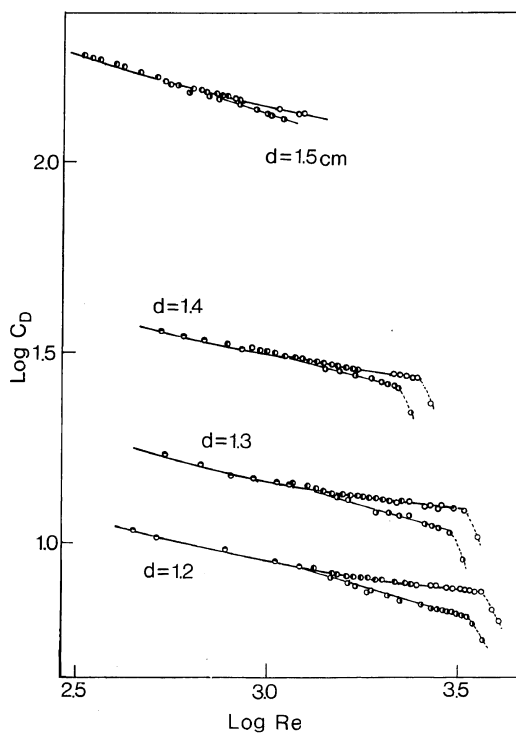


Figure 1. $\log C_D$ plotted against $\log Re$ for simple fluids and 93.1 ppm solutions of IK-1500 in benzene, measured with steel balls of various sizes at 25°C : \circ , benzene; \bullet , water; \bullet , water-glycerol; \bullet , 93.1 ppm. D is 1.578 cm.

practically be represented by an experimental $\log C_D$ vs. $\log Re$ plot. Hubbard and Brown showed that this plot in the laminar region gives a straight line of slope -1 and that in the turbulent region follows a smooth concave curve. The $\log C_D$ vs. $\log Re$ data

for simple liquids (benzene, water, water-glycerol) showed features characteristic of the turbulent flow, as can be seen from Figure 1. Moreover, these data could be reduced to a single curve. On the other hand, the data for the 93.1 ppm solution for various ball diameters fell below the lines for simple Newtonian fluids. This is a clear demonstration of drag reduction. The Reynolds number at the onset of drag reduction was obtained from the intersection of the two straight lines fitting the data points

for the simple liquids and the polymer solution. Figure 1 shows that Re at the onset of drag reduction decreases as the ball diameter increases or as the equivalent diameter defined by eq 3 decreases. Similar results were obtained for pipe flows of other polymers.^{2,8}

Concentration Effects on Drag Reduction

Figure 2 shows the Re dependence of the drag coefficient obtained with the 1.2 cm ball for polymer

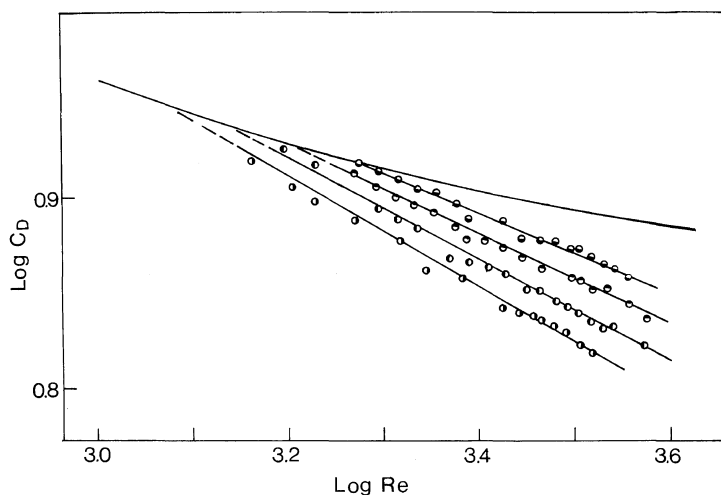


Figure 2. $\log C_D$ plotted against $\log Re$ for various concentrations of IK-1500 in benzene at 25°C. D and d are 1.57₈ and 1.2 cm, respectively; ○, benzene; ◐, 11.6; ◑, 23.3; ◒, 46.6; ◓, 93.1 ppm.

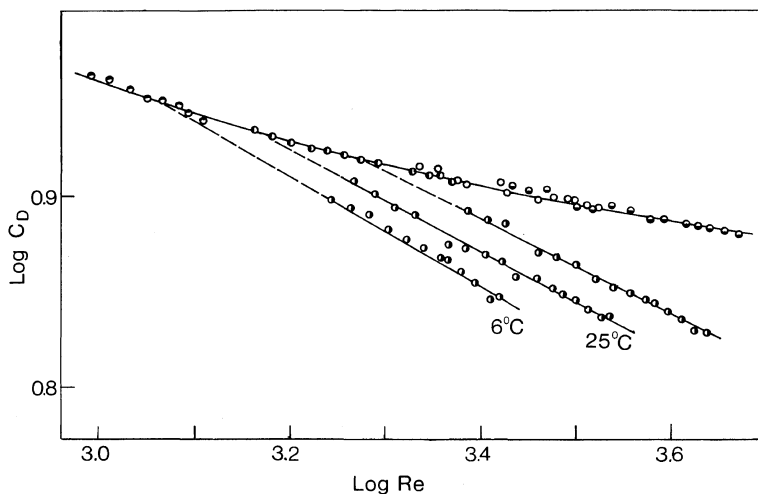


Figure 3. $\log C_D$ plotted against $\log Re$ for simple fluids and 46.6 ppm solutions of IK-1500 in benzene at various temperatures: ◐, benzene at 45°C; ○, benzene; ◑, water; ◒, water-glycerol at 25°C; ◓, 46.6 ppm. D and d are 1.57₈ and 1.2 cm, respectively.

solutions and simple liquids. It can be seen that the values of $\log C_D$ decrease linearly with increasing $\log Re$ and that the absolute value of the slope increases as the polymer concentration increases. The Re at the onset of drag reduction is listed in Table I. This critical Re decreases with increasing polymer concentration, in conformity with the currently available experimental data for the pipe flow.³

Temperature Effect on Drag Reduction

Figure 3 illustrates the temperature effect on drag reduction. The C_D vs. Re data for benzene at various temperatures fall on a single curve. On the other hand, data for the 46.6 ppm solution show temperature-dependent behavior. The Reynolds number at the onset of drag reduction as a function of temperatures is given in Table I.

In summary, the present study shows that drag reduction occurs at a lower Re as the equivalent diameter decreases, the polymer concentration increases, and the temperature decreases, in the case of ultrahigh-molecular-weight polystyrene in benzene. In particular, the Re at the onset of drag reduction was found to be a function not only of the equivalent diameter and the polymer concentration but also of temperature. Thus, the dimension and

deformability of polymer coils in solution may be responsible for the onset of drag reduction.

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