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TURBULENT FLOW OF AQUEOUS SOLUTIONS OF MICELLE-FORMING SURFACE-ACTIVE SUBSTANCES IN GAPS BETWEEN COAXIAL CYLINDERS

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The results of experimental investigations of turbulent friction reduction by additives in a gap between coaxial cylinders are given.

Some micelle-forming surface-active substances (SAS), as well as high polymers, are able to reduce the frictional drag of fluids. There have been a number of studies of turbulent drag reduction by SAS additives in tubes [1, 2]. A correlation between the onset of drag reduction and the micellar nature of SAS has been established [3], and the feasibility of using them for reduction of drag in homogeneous and suspension-laden flows has been demonstrated [4]. Several questions connected with the use of SAS additives for reduction of turbulent friction, however, are still unresolved.

In the present work we investigated the drag torque in relation to Reynolds number for flows of aqueous solutions of Ditalan OTS and Metaupon in the gap between coaxial cylinders, i.e., in conditions in which a particular friction stress can be maintained at the wall over a long period.

The experimental investigations were made on an apparatus consisting of a stainless steel cup within which three cylinders were fitted coaxially with the cup at a distance of 1 mm from one another. The upper and lower cylinders were kept stationary to eliminate end effects. The middle cylinder could rotate through 120°, and the torque developed on it due to rotation of the outer cylinder was transmitted to a force gauge, from the readings of which the drag torque was calculated from the equation

$$C_m = \frac{\tau}{\rho U^2} = \frac{M}{\rho\omega^2}\,\frac{1}{2\pi R^4 H}.$$

The Reynolds number was determined from the equation

$$\mathrm{Re} = U\delta/\nu = \omega R\delta/\nu.$$

Figure 1 shows the drag torque as a function of Re for an aqueous 1% solution of Ditalan OTS containing different concentrations of sodium chloride.

Research on the effect of additions of electrolytes on the hydrodynamic effectiveness of SAS solutions is of great interest, since it is known that their presence greatly reduces the concentrations of SAS at which spherical and anisometric structures composed of individual SAS molecules (ions) are formed. The Reynolds number was calculated from the viscosity

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of the water. It is apparent that the addition of electrolyte increases the hydrodynamic effectiveness of the solution. At a sodium chloride concentration C = 1.25% (curve 2) there was a slight reduction of drag, and the drag torque was practically the same as for water (curve 1). An increase in sodium chloride content to 3% led to a greater reduction of C_m and at Re = 20,000 it became $4 \cdot 10^{-4}$, i.e., it was reduced to half of that of water. Hence, for Ditalan OTS solutions micelle formation occurs only when an electrolyte is present. If sodium chloride is used the optimal concentration in the solution is 3%.

Figure 2 shows plots of the drag torque against Re, calculated from the viscosity of the water, for solutions of Ditalan OTS of different concentrations containing 3% sodium chloride. Curves a and b represent the relation $C_m = f(\mathrm{Re})$ for a flow of water in the gap between coaxial cylinders of relative width $\delta/R = 0.028$, obtained by G. I. Taylor (see reference in [5]). It is apparent that for Re < 3500 the drag torque for a solution of concentration C = 0.3% (curve 2) has higher values than for water (curve 1). Doubling of the concentration of Ditalan OTS (curve 3) leads to an increase in C_m in the laminar flow region, but the greatest drag reduction, corresponding to a minimum value of C_m, is obtained at Re = 20,000. For solutions with C = 1.2 and 2.4% (curves 4 and 5, respectively) drag reduction becomes apparent at Re = 6000 and 9000, but these solutions can effect maximum drag reduction at much greater shear stresses.

We conducted similar investigations with Metaupon solutions. The curves of $C_m = f(\mathrm{Re})$ for aqueous solutions of Metaupon were of the same nature as those for Ditalan OTS. The addition of Metaupon, however, was more effective at higher shear stresses. This suggests that the structural and mechanical properties of SAS solutions and, hence their hydrodynamic effectiveness depend significantly not only on the concentration of the additive but also on the structure of the hydrocarbon radical of the SAS.

Hysteresis effects on plots of the drag torque against Re in aqueous solutions of Ditalan OTS containing 3% sodium chloride were also investigated. It was found that the relations between C_m and Re in the equilibrium state (i.e., when the experimental points were obtained when the drag reduction effect was stabilized in time) differed from the corresponding relations for the nonequilibrium state. The difference was particularly pronounced when the curves were recorded when Re was reduced after overstressing of the solution (i.e., after Re at which the solution lost its drag-reducing ability). For instance, an aqueous 6% solution of Ditalan OTS in the early stages of a prescribed turbulent flow regime exhibited greater drag throughout the investigated range of Re than a solution in the equilibrium state. It should be noted that the equilibration of SAS solutions depends not only on the concentration and kind of SAS, but also on the temperature of the solutions, added electrolyte, etc. For instance, in Metaupon solutions the recovery of hydrodynamic effectiveness at equal SAS concentrations was 2-3 times more rapid than in Ditalan OTS solutions, which can be attributed to the greater micelle-forming ability of its surface-active ions.

The obtained results can be explained in the following way. According to current ideas in physicochemical mechanics [6], there are two mechanisms responsible for stimulation of the flow of disperse systems. They are essentially orientation effects in systems containing kinetic units of anisotropic elongated form and direct destruction by shear stress.

It can be surmised from the above account that at low shear stresses practically intact anisometric structures (layered micelles) are present. An increase in SAS concentration increases the strength of such structures, but this is accompanied by an increase in viscosity of the solution, which is the reason for the increase in drag torque. An increase in Re (for constant SAS concentration) leads to a transition to a flow region in which the structures are broken up into separate aggregates (fragments of the continuous micellar layers), which constitute the main kinetic units of the flow. The average velocity gradient causes orientation of the aggregates with their major axis in the direction of flow, which leads to the appearance of viscosity anisotropy in the solution and hence, as the authors of [1] suggest, to drag reduction. Increase in tangential stress leads to breakup of the aggregates to a size corresponding to the equilibrium size for the particular gradient. The equilibrium state is due both to reduction of the arm of the moment acting on the aggregates during their destruction and to some strengthening of the aggregates by an increase in the fraction of stronger bonds as a result of rupture of the weaker ones.

With further increase in shear stress the drag torque sharply increases and the solution subsequently behaves like the solvent. The explanation of this is that on attainment of a particular Re for each SAS concentration the anisometric micellar structures are completely

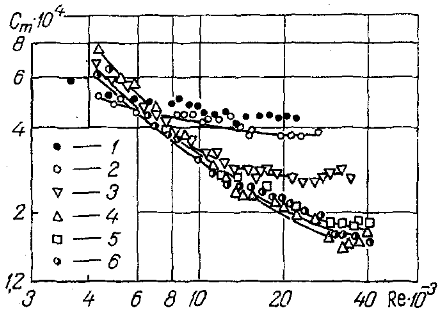

Fig. 1

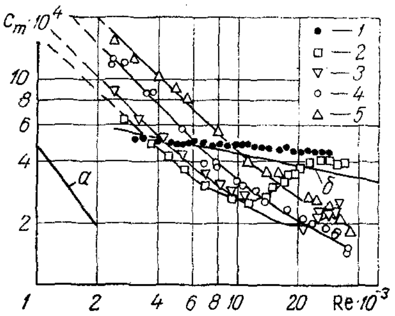

Fig. 2

Fig. 1. Effect of electrolyte concentration on plot of drag torque against Re for water (1) and aqueous 1% solution of Ditalan OTS. Sodium chloride content: 2) 1.25; 3) 1.5; 4) 1.75; 5) 2.0; 6) 3.0%.

Fig. 2. Plots of drag torque against Re for aqueous solutions of Ditalan OTS containing 3% sodium chloride: 1) water; 2,3,4,5) Ditalan OTS concentration in solution 0.3, 0.6, 1.2, and 2.4%, respectively.

reduced to less complex spherical structures (or even to initial SAS molecules), which rules out the appearance of viscosity anisotropy.

Thus, the addition of micelle-forming SAS can significantly reduce (sometimes by 60%) the drag in a turbulent flow of fluid in the gap between coaxial cylinders. It has also been established that the structural and mechanical state of the solution has a significant effect on drag reduction in SAS solutions. Hence, the construction of a model of the mechanism of drag reduction requires not only a consideration of the orientation of anisotropic micellar structures, but also their breakup.

NOTATION

C_m, drag torque; Re, Reynolds number; τ, mean friction stress on cylinder wall; ω, angular velocity of outer cylinder; R, internal radius of outer cylinder; H, height of inner cylinder; ρ, density of investigated fluid; M, hydrodynamic friction moment; δ, width of gap between cylinders; ν, kinematic viscosity of water.

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