REDUCTION OF HYDRODYNAMIC DRAG IN PIPELINES

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A method of reducing hydrodynamic drag based on the addition of high-polymer surface-active agents is examined. An attempt is made to explain the mechanism of this phenomenon, and a method of selecting additives is proposed.

The hydrodynamic drag that develops when a solid surface is in contact with a turbulent stream of liquid is due to molecular and molar momentum transfer effects. Molar transfer in a turbulent stream is due to turbulent fluctuations and quantitatively determines the energy dissipation in such a stream [1].

Recent investigations have shown that energy dissipation in a turbulent stream may be decreased appreciably by addition of certain high-polymer compounds [2–4, 10–12].

There is a need to furnish an explanation of the nature of this phenomenon and to make available a method of choosing the optimum additives to decrease the hydrodynamic drag of the system, depending on the kind of liquid and the flow regime. The occurrence of turbulence in a liquid stream under appropriate conditions is explained [15] by disturbance of the laminar flow stability by perturbations entering the system from outside or arising within it at a phase interface.

The stability of a laminar flow may be increased by increasing the liquid viscosity or by altering the stream structure, when a body of liquid is transformed into a quasi-solid. Although there is then damping of turbulent fluctuations randomly introduced into the system and disturbance of the laminar flow is not observed, the hydrodynamic drag may not be lowered, but, on the contrary, may increase. This is the picture encountered in ordinary rheological systems whose hydrodynamic drag exceeds that of the original Newtonian liquid without rheological additives (clay slurry). However, it appears to be possible to create a rheological system in which the hydrodynamic drag will be less than in the original Newtonian liquid. For this it is necessary that the rheological additive should create nonuniform viscosity in the liquid stream, the viscosity being, in fact, greater in the core of the stream, where the development of turbulent fluctuations is most probable, and less near the wall, where the principal deformation of the liquid occurs, and where there consequently is an appreciable increase in velocity gradient and in viscous friction [16].

High-molecular compounds (lyophilic polymers), as surface-active agents for a given system, may act as additives for generating selective viscosity in the liquid, i.e., viscosity higher in the stream core and lower near the wall. For example, for polar liquids (water, etc.), high polymers whose molecules contain polar groups (carboxymethyl cellulose, etc.) may serve as additives. When such polymers dissolve in a liquid, true solutions are formed, i.e., homogeneous systems that are thermodynamically in equilibrium and stable. The structural unit of such solutions is composed of solvated macromolecules of high-polymer compound, which cannot be observed even under the ultramicroscope [6–9]. The increased viscosity and changed structure of the stream when the high polymers dissolve in the liquid may be due to polar, hydrogen and other molecular or chemical forces arising between molecules in the solution, to solvation, to intertwining of long molecules, or to other factors. The rheological properties of high-polymer solutions have been studied in detail by Rebinder et al. [9]. It has become evident from these investigations that the viscoelastic properties of such solutions are due in the first instance to peculiarities of the molecular structure of high polymers, and that the reduction of their specific flow properties to solvation of the macromolecules alone is a crude approximation.

The result of the flow's acquiring a structure and of the increased liquid viscosity, as shown above, is a damping of turbulent fluctuations in the core and an increase of laminar stability of the stream. At the same time, at the flow periphery (in a thin layer at the wall), the viscosity is lowered, and an effective slip velocity at the wall [13] is created by the orienting action of the unbalanced molecular field at the solid wall surface on the molecules of the solution. This hypothesis is confirmed by the nature of the velocity profile in a pipe with a flow of pseudoplastic rheological liquids—a constant velocity in the stream core and a sharp fall in velocity at the wall [13].

For particular rheological solutions, slippage of the stream at the wall has been observed. In this case the shear velocity near the wall (y = 0) will differ from its value outside the anomalous flow region (which region is usually very small) by an amount depending on distance [13]

$$\frac{dw}{dy} = f(\tau) + g(\tau, y), \tag{1}$$

where the function $g(\tau, y)_{y>\varepsilon} = 0$ (ε is the thickness of the slip layer).

It follows from (1) that slippage favors lowering of the hydrodynamic drag.

Adsorption of high-polymer surface-active molecules on the tube wall and a corresponding orientation of molecules in the layer at the wall may not only lower the liquid viscosity near the wall and create a slip effect, but also promote damping of turbulent fluctuations entering from outside, as well as hindering formation of eddies at the wall.

The proposed scheme also agrees with the known fact that wettability of the tube wall has no influence on hydrodynamic drag [18]. Indeed, in this case there is no damping of turbulent fluctuations in the flow core arising from energy dissipation. Then, because of the reduced stabilizing action of the walls, the length of the stabilizing section (L_{st}) increases, and, when $L < L_{st}$, the lower critical Re number* [17] is reduced, which eliminates even the small positive effect which, according to [13], is produced by slip of the liquid at the wall.

Turning now to the choice of the optimum additive to promote reduction of hydrodynamic drag, it should be noted that lyophobic polymers and inert colloidal particles cannot produce the effects described above, and therefore cannot promote reduction of hydrodynamic drag. Moreover, systems with such additives are thermodynamically unstable, and to stabilize them requires the addition to the system of additional stabilizing surface-active components. It may thus be asserted that additives to lower hydrodynamic drag should be surface-active substances. The complexity of the mechanism of the phenomenon renders it impossible at the present time to give a purely analytical explanation of the optimum type of additive as a function of the physical and chemical properties of the system and of the flow regime parameters. For this reason it is expedient to use the rheological properties.

In rheology a power dependence is assumed between shear stress and shear rate in a liquid:

$$\tau = k\dot{\gamma}^{n}. \tag{2}$$

For an internal flow problem it is more convenient to write (2) in the following form [5, 13]

$$\tau = D\Delta P_{r}/4L = k'(8w_{m}/D)^{n'}. \tag{3}$$

From (3) we determine the pressure loss of a section of pipe of length L to be

$$\Delta P_{r} = \frac{4L}{D}k'\left(\frac{8w_{m}}{D}\right)^{n'}. \tag{4}$$

The exponent n' and coefficient k' in (4), called the behavior and consistency indices of the liquid, respectively, depend in the general case on the friction stress τ, and are determined from the formulas [13]

$$n = n'\left[1 - \frac{1}{3n'+1}\left(\frac{dn'}{d\ln\tau}\right)\right]^{-1},$$
$$k' = k[(3n+1)/4n]^{n}. \tag{5}$$

In some cases n' may be assumed to be independent of τ (in a narrow range of γ). Then, according to (5),

$$n' = n. \tag{5a}$$

Thus, knowing the rheological coefficients n and k of the liquid, or values close to them in the sense of n' and k', we may determine the pressure loss ΔP_r from (4). Accordingly, for a Newtonian loss ΔP_r pressure loss in a pipe of diameter D and length L may be determined from the formula

$$\Delta P_{N} = \lambda\frac{L}{D}\frac{w_{m}^{2}}{2}\rho. \tag{6}$$

In the case when transition from a newtonian liquid to a rheological one results from addition of surface-active polymer to the liquid, the hydrodynamic drag in the pipe will be decreased:

$$\Delta P_{N} > \Delta P_{r}. \tag{7}$$

Substituting values of ΔP_r and ΔP_N from (4) and (6) into (7), we obtain

$$\lambda w_{m}^{2}\rho/2 > k'(8w_{m}/D)^{n'}. \tag{8}$$

We shall introduce the concept of generalized mass flowrate of liquid through the pipe:

$$q = Q(\pi D^{3}/6)^{-1}. \tag{9}$$

The quantity q denotes liquid mass flowrate through a pipe of diameter D, expressed as the number of spheres with diameter equal to that of the pipe.

We transform (8), taking (9) into account, and assuming, according to Blasius, that $\lambda = 0.3164\cdot\mathrm{Re}^{-25}$; obtain

$$q > a\left(\frac{k'}{D^{1.5}\rho\nu^{0.25}}\right)^{\frac{1}{1.75-n'}}, \tag{10}$$

where

$$a = 3\cdot 2^{\frac{4n'+1,25}{1.75-n'}}\cdot 0.3164^{-\frac{1}{1.75-n'}}.$$

From (10), according to the rheological properties of the surface-active polymer solution and to the main characteristics of the system (λ, ρ, D), we may determine the range of conditions in which reduced hydrodynamic drag will occur.

It should be noted that reduction of hydrodynamic drag may occur only in a region of developed turbulent flow, when the effect of slip and damping of turbulent fluctuations exceeds the increase of drag due to viscosity increase upon addition of high-polymer [16].

As an example, we shall examine a system consisting of a smooth tube of diameter D = 0.05 m and 0.1 m, along which flows water at temperature t = 10° C. As the additive to reduce friction, we shall take carboxymethyl cellulose with concentration c = 0.7%. Tentative values of the rheological constants may be taken from [13]. Calculations according to (10) show that we should expect reduced hydrodynamic drag for a generalized mass flow q > 240 at diameter 0.05 m, and q > 87 at diameter 0.1 m.

The method described may find application in the preliminary choice of high-polymer surface-active

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*The reduction of the lower critical Re number on lyophobization of the tube wall has been attributed by Perel'man to lowering of the effective viscosity of the liquid stream.

additives to reduce hydrodynamic drag in given systems.

NOTATION

w—liquid flowrate; $\dot{\gamma}$—shear rate; τ—shear stress; k(k')—rheological property of diluted material; n(n')—rheological behavior index of liquid; ΔP—hydrodynamic drag; D—tube diameter; L—tube length; Q—liquid mass flowrate; λ—friction coefficient of pipe; ρ—density of liquid. Subscripts: m—mean, r—rheological.

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