REDUCTION OF HYDRAULIC LOSSES BY ADDITIONS OF SURFACTANTS

V. M. Dobrychenko, V. G. Lobachev, I. L. Povkh,
and A. E. Eidel'man

UDC 532.517.4

A reduction in the hydrodynamic resistance in large-diameter tubes is achieved by the addition of industrial surfactants. The relation of this effect to the rheological properties of the solutions is noted.

At present, investigations into the laws of motion of viscous liquids are being conducted in parallel with the study of the effect of additives that reduce hydrodynamic resistance on the behavior of turbulent flows. These researches are associated with the tendency to use the phenomenon of resistance reduction in a series of practical applications – hydrotransport, the flow of petroleum along pipelines, drilling and fire-fighting equipment, etc. – and also as an additional means of studying the motion of viscous media [1].

At the present time, additives that are known to reduce hydraulic losses include solid particles, polymers, and certain surfactants [2]. Polymers are highly effective in small concentrations, but their susceptibility to mechanical, thermal, bacterial, and oxidative destruction has so far considerably hindered their practical use. In addition, some forms of polymer lose their ability to reduce hydrodynamic resistance in the presence of electrolytes and solid suspensions in the solution [3].

Studies already carried out have used both surfactants which enter into reactions with dissolved salts – for example, sodium oleate [4] – and those which do not – a mixture of ammonium cetyltrimethylbromide and 1-naphthol [5]. We propose to attempt the reduction of hydrodynamic resistance by means of surfactants that are widespread in industry and have good engineering properties – sufficiently high solubility, stability against dissolved salts, lack of corrosive action on metals, etc. – and to investigate the laws of motion of solutions of these surfactants.

The experimental conditions are given in Table 1.

The temperature of the solution was maintained in the range 15-20°C. The apparatus, with tubes of diameter 104 and 202 mm, worked in a closed cycle.

The following surfactants were investigated: sulfonol, sulfonate, Progress, OP-7, ditalane E, ditalane OTS, and metaupone. Reduction in resistance (RR) was observed for the last two, in the presence of the electrolyte sodium chloride. These surfactants are in the form of pastes with the following composition:

TABLE 1. Experimental Conditions

Tube diameter, mm	Tube material	Method of tube construction	Length of meas. section, m	Method of measuring velocity	Source of motion
6,23	Stainless steel	Seamless	2,2	Volumetric	Gravity
104	Glass	Using sleeves	15,0	Venturi tube	Centrifugal pump
202	Carbon steel	Welding	30,0	Venturi tube	Centrifugal pump

Donets State University. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 30, No. 2, pp. 240-245, February, 1976. Original article submitted December 20, 1974.

Ditalane OTS	
ammonium sulfoether	40%
polyethylene glycol	2%
urea	5%
polyphosphate	2%
water	51%

Metaupone	
sodium oleinmethyltauride	32%
sodium chloride	10%
sodium hydroxide	0.5%
water, to	100%

The curves in Fig. 1, constructed from experimental results for a tube of diameter 6.23 mm with $\mathrm{Re} = 2.7 \cdot 10^4$, show that the concentrations of both the surfactant and the sodium chloride affect the RR. It is a feature of curve 1 that it does not pass through the origin when the RR is zero. The shape of curve 1 indicates a sharp change in the liquid properties when the surfactant concentration is several times larger than the threshold. In the experiment, the maximum RR was 63% for ditalane-OTS concentrations of 0.5-1.0%. The decrease in RR with further rise in the surfactant concentration is associated with increase in viscosity.

As also seen in Fig. 1, the size of the RR changes with change in the sodium chloride concentration, for constant concentrations of ditalane OTS and metaupone in the moving solution. In the solutions of ditalane OTS and metaupone, the RR is observed at different electrolyte concentrations.

In carrying out the experiments, the solutions were observed to become significantly thicker and more structured in the range of sodium chloride concentrations in which the RR was observed. This was confirmed by viscosity measurements on a capillary viscometer, shown by curve 5 in Fig. 1. Comparison of curves 2, 3, and 5 shows that the appearance of the RR depends on the development of structure in the solution, which also leads to the increase in viscosity. It should be noted that in the experiments with surfactants which did not reduce the hydrodynamic resistance, no thickening of the liquid was observed.

The dependence $\lambda = f(\mathrm{Re})$ is shown in Figs. 2 and 3 for different conditions of motion of the ditalane-OTS solution. We note the following features of the data shown in Fig. 2. For laminar motion, increase in surfactant concentration leads to increase in resistance, evidently as a result of increase in viscosity. The velocity at which stability is lost and the RR begins to appear increases with rise in surfactant concentration. In addition, increase in surfactant concentration shifts the RR zone in the direction of higher Reynolds numbers and at the same time the size of the RR increases.

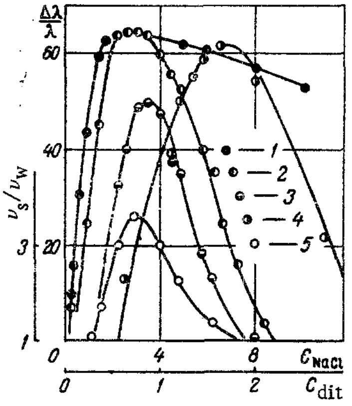

Fig. 1

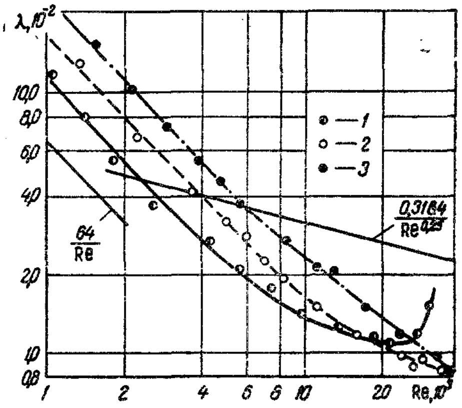

Fig. 2

Fig. 1. Reduction in resistance as a function of ditalane-OTS concentration, %, for constant electrolyte concentration 3.5% (1); as a function of electrolyte concentration, %, for constant ditalane-OTS concentrations of 0.7% (2) and 0.3% (3) and for constant metaupone concentration 0.5% (4); viscosity of 0.5% solution of ditalane OTS as a function of sodium chloride concentration (5).

Fig. 2. Motion of solution containing 3% sodium chloride in a tube of diameter 6.23 mm for ditalane-OTS concentrations of 0.35 (1), 0.7 (2), and 1.5% (3).

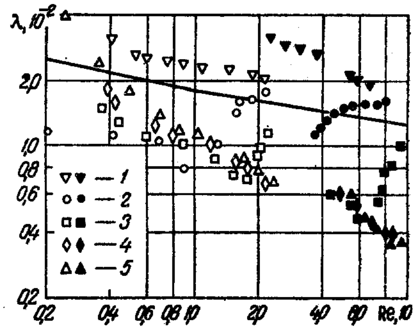

Fig. 3. Motion of pure water (1) and solutions of ditalane-OTS of concentrations 0.5 (2), 1.0 (3), 1.5 (4), and 2.0% (5) for sodium chloride concentration 3%, according to the results of measurements in a 104-mm tube (open symbols) and in a 202-mm tube (filled symbols).

The latter effect is also observed in the experiments shown in Fig. 3. Here it is also seen that in the larger-diameter tube the reduction and disappearance of the RR occurs at higher Reynolds numbers. This may be explained by the smaller shear stress in tubes of larger diameter at the same Reynolds numbers. It should be noted that a similar relation between the Reynolds number at which RR decreases and the size of the tube was found in [6]. For tubes of all diameters, the properties of the solution are restored on reducing the flow velocity.

The experimental points corresponding to the motion of pure water in Fig. 3 lie above the classical curve for smooth tubes, which may be explained by the presence of joints on the measuring section and also by the roughness of the steel tubes. A comparison of the RR obtained in smooth glass and rough steel tubes (Fig. 3) shows that the RR is larger in steel tubes. Hence, the effect of roughness on the flow is neutralized by the surfactant additive, evidently as a result of the thickening of the viscous surface layer.

Visual observations in glass tubes and in transparent insertions in steel tubes showed that turbulent motion of the surfactant solution is accompanied by the presence of schlieren effects. This phenomenon is associated with the stick-like shape of the micelles; when, in the shear flow, their axes are perpendicular to the incident rays, the micelles strongly scatter the light, so that the currents become visible in the form of silk-like threads [7]. The schlieren effect confirms the assumption of [8] that the presence of stick-like particles facilitates the RR.

The motion of ditalane-OTS solutions without additions of sodium chloride is also associated with a schlieren effect, but the same hydraulic losses occur as in the motion of pure water. Hence, the presence of micelles is a necessary but not sufficient condition for the appearance of RR. The further requirement is the structuring and thickening of the surfactant solutions which occur in the presence of the electrolyte.

The schlieren effect may serve as a good visual indicator of the occurrence of velocity pulsations and the onset of developed turbulence in the motion of optically transparent media. In observations on glass tubes, it is found that increase in the velocity of flow is accompanied by the appearance of individual centers of turbulence, their growth and coalescence, and the onset of total developed turbulence.

The transitional zone for solutions containing 2% ditalane and 3% sodium chloride lies in the range of Reynolds numbers from 25,200 to 85,000. As is evident from Fig. 3 (curve 5), in this range there occurs the most rapid increase in RR, which slows down in the turbulent region. Because of the technical limitations of the apparatus, it is not possible to attain velocities at which the disappearance of RR is observed, as for solutions with lower ditalane-OTS concentrations.

The schlieren effect also gives an idea of the structure of the developed turbulence. In our observations, we noted a greater number of large perturbations in solutions moving with RR and an almost total lack of small eddies, in contrast to solutions whose hydrodynamic resistance was not reduced.

Investigation of the rheological properties of the studied solutions showed that they have non-Newtonian properties and behave as pseudoplastics described by the power law [9]

$$\tau = k\gamma^{n}.$$

Measurements using a capillary viscometer for solutions with identical sodium chloride content (3%) and different ditalane-OTS concentrations showed that increase in surfactant concentration leads to decrease in the index n and increase in the consistency k (Fig. 4). This rise in the pseudoplastic properties due to strengthening of structure formation in liquids is the cause of the later turbulization and increase in the shear velocities at which decrease and disappearance of the RR occur.

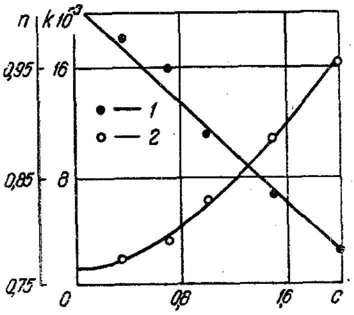

Fig. 4. Curves of the index of non-Newtonian behavior n (1) and consistency k, 10^{-3} (2) versus ditalane-OTS concentration in 3% NaCl solution.

When the surfactant concentration in the solution reaches the critical concentration for micelle formation (CCM), the properties of the solution change sharply [10]. This is associated with the appearance of non-Newtonian properties, shown in Fig. 4 by the deviations of the value of k from μ (at the experimental temperature 18°C) and of the value of n from unity, for ditalane-OTS concentrations close to its CCM, equal to 0.05% for a sodium chloride concentration of 3%.

In solutions with 3.5% sodium chloride (Fig. 1), the appearance of RR occurs at a ditalane-OTS concentration close to its CCM in solutions with that sodium chloride concentration, which lends support to the hypothesis that the reduction of hydraulic resistance in surfactant solutions is associated with the micelles.

In surfactant solutions, there occur complex physicochemical processes – including particle interaction and hydration and intra- and intermolecular immobilization of the solvent – which become more intense at optimum electrolyte concentration. This leads to the appearance of supermicellar structural formations which are the cause of the increase in viscosity and the appearance of non-Newtonian properties in the solution.

The dimensions of these formations are comparable with the dimensions of the very largest turbulent perturbations. This explains why the reduction in hydrodynamic resistance begins at once on loss of stability of the flow. In contrast to polymer solutions, in which macromolecules can interact only with small-scale eddies appearing at relatively high velocities, in structured surfactant solutions the threshold Reynolds number coincides with the critical value. The absence of small perturbations, which is observed in flows moving with reduced resistance, is due to the suppression of small-scale turbulence.

In the motion of liquid flows, two processes occur simultaneously: the disruption and the restoration of supermicellar structure. With increase in velocity, the intensity of the first process increases and as a result, at sufficiently high shear stress, the magnitude of the RR is sharply reduced. Decrease in velocity and shear stress leads to recovery of structure and growth in the RR. Appropriate choice of surfactant and electrolyte concentrations can ensure the conditions for liquid motion in the range of Reynolds numbers corresponding to minimal hydraulic losses.

NOTATION

C, mass concentration; f, function; k, consistency; n, index of non-Newtonian behavior; Re, Reynolds number, based on water viscosity; γ, shear velocity; Δ, increment; λ, coefficient of hydrodynamic resistance; ν_w, kinematic viscosity of water; ν_s, kinematic viscosity of solution; τ, shear stress.

LITERATURE CITED

1. A. Yu. Ishlinskii, Inzh.-Fiz. Zh., 25, No. 6 (1973).
2. G. K. Patterson, J. L. Zakin, and J. M. Rodriguez, Indust. Eng. Chem., 61, No. 1 (1969).
3. J. G. Savins, Method of Decreasing Friction Loss in Turbulent Liquids, US Patent No. 3,361,213 (1968).
4. J. G. Savins, Rheologica Acta, No. 6 (1967).
5. J. L. Zakin, M. Poreh, A. Brosh, and M. Warshavsky, Chem. Eng. Progress Symp. Ser., 67, No. 111 (1971).
6. A. White, Nature, 214, No. 6 (1967).
7. I. N. Putilova, Handbook of Practical Applications of Colloidal Chemistry [in Russian], Goskhimizdat, Moscow–Leningrad (1948).
8. I. L. Povkh. A. B. Stupin, V. M. Dobrychenko, and S. N. Maksyutenko, Inzh.-Fiz. Zh., 27, No. 4 (1974).
9. B. M. Smol'skii, Z. P. Shul'man, and V. M. Gorislavets, Rheodynamics and Heat Transfer of Nonlinear Viscoplastics [in Russian], Nauka i Tekhnika, Minsk (1970).
10. K. Shinoda, T. Nakagawa, B. Tamamushi, and T. Isemura, Colloidal Surfactants, Academic Press (1963).