OBLITERATION OF CAPILLARY CHANNELS IN THE FLOW OF MINERAL OILS

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The flow of commercial and purified vaseline oil (MVP) through capillary channels is studied experimentally; data relating to the concentration of solid dispersed particles in the oils are presented. The blocking of the capillaries is determined by coagulation processes which intensify in a hydrodynamic flow.

It was shown earlier [1] that, under certain circumstances, in the absence of marked structure-formation, the flow of commercial oils through capillary channels failed to obey the Poiseuille law; the volumetric rate of flow gradually diminished and tended to zero. This phenomenon has been given the name of "obliteration" [2] and has been studied in detail by a number of authors [3, 4]. The obliteration process is determined by a number of parameters: the rheological properties of the oils, the existence of polar molecules inclined toward micelle formation and adsorption on the interface with the solid material, the concentration and dimensions of impurity particles dispersed in the oil, and so forth [5]. Despite the wide variety of factors determining flow through narrow channels, the sharp reduction in the flow of liquid must be associated with the development of an ordered structure of high mechanical strength in the capillaries as a result of processes involving particles of the dispersed phase in the mineral oils. This paper is concerned with the study of this problem.

Microscope and ultramicroscope examinations have shown that, in those cases in which obliteration occurs, the oil contains a comparatively large quantity of suspended particles (Fig. 1). The number and size of the dispersed particles per unit volume of oil are determined by a microscope method in linearly-polarized light, using the method of [6]; quantitative estimates of the impurities in various oils are presented in Table 1.

We measured the flow of liquid through capillaries of regular geometrical form using a standard hydrostatic press [7]. The apertures of the capillaries were prepared by the electric-spark machining of a brass block, and also by drawing from a glass tube. The cleanliness of the capillary before and after the experiment was checked under the microscope. We principally studied oils of the MVP type, both in the ordinary commercial state and also when purified by silicagel and repeated filtration through finely porous paper filters. In addition to this, we studied suspensions of graphite, quartz, and aluminum in purified oil. The concentration of the dispersed phase was no greater than 0.1 wt.% in any of the experiments. The suspensions were prepared by crushing the materials in a porcelain mortar in the presence of the

TABLE 1. Concentration of Dispersed Particles of Various Sizes in Commercial and Purified Oils

Oil	Particle concentration, 1/cm³			
	less than 2 μ	2-5 μ	5-10 μ	more than 10 μ
Vaseline (MVP), commercial	420000	180000	12000	9500
Spindle (AU), commercial	160000	120000	39000	30000
Diesel (MT-16p), commercial, with additive	1500000	120000	90000	19000
Vaseline (MVP), purified	65000	individual particles	—	—

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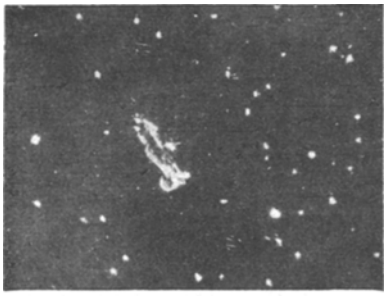


Fig. 1

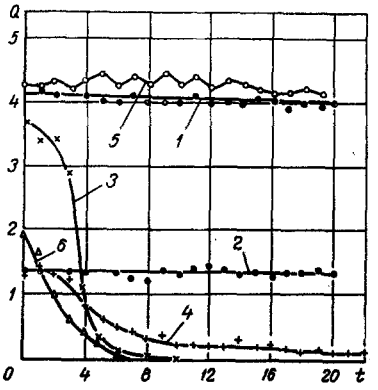


Fig. 2

Fig. 1. Microscope photograph of particles in commercial oil taken with crossed polaroids.

Fig. 2. Dependence of the volumetric (Q, cm^3/min) flow of liquid on the time of flow (t, min) for various pressure drops in a brass capillary: 1, 2) purified; 3)-5) commercial oil; 6) water/oil emulsion, 1.0 vol. %; 1), 3), 5), 6) 1.55 kg/cm^2; 2), 4) 0.55 kg/ cm^2.

dispersion medium, with subsequent dilution to the specified concentration. The quality of the dispersion was checked under the microscope and ultramicroscope; particles and aggregates with a diameter of over 10μ were not allowed. An emulsion of distilled water in purified oil with a concentration of 1.0 vol.% was prepared by ultrasonic dispersion.

The electrokinetic potential was measured by the moving-boundary method in a Cohn apparatus with platinum electrodes and filtrates of the suspensions as auxiliary liquids. The value of the ζ-potential was close to zero.

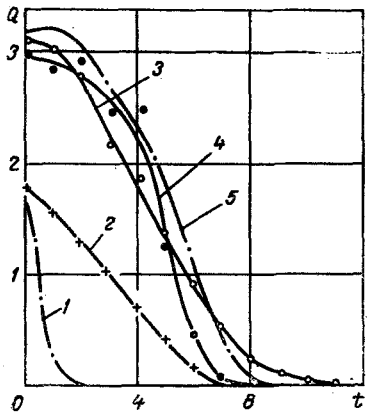
Figure 2 characterizes the outflow of liquids through a metal capillary of diameter 105 μ and length 1 mm. We see from the curve that for purified oil (curves 1, 2) the volumetric flow is relatively constant, only changing within the limits of experimental error over a period of 20 min. The Q = f(t) characteristic of commercial oil (curves 3, 4) has three parts: first one with a slowly-varying Q, then one with a sharp fall in flow velocity, and then a third sloping part immediately preceding the stoppage of the flow of liquid. The shape of the curve and the time required for the complete stoppage of the capillary largely depend on the external pressure.

Analogous laws are observed in the flow of graphite suspensions of various concentrations, quartz, and aluminum in purified oil (Fig. 3, curves 1-5) and also water–oil emulsion (Fig. 2, curve 6). In a glass capillary 95μ in diameter and 50.0 mm long, however, commercial oil flows at a constant rate for 25 days for a pressure drop of 0.05 kg/cm^2.

As the dispersions flow through the capillary, particles are deposited on the walls, chiefly at the ends of the channel, and mainly on the side of the mouth (aperture) as indicated in Fig. 4; these reduce the hydraulic conductivity of the system. The thickness of the structured layer on the inner surface of the capillary increases gradually, since the radius of the latter is more than an order of magnitude greater than the dimensions of the dispersed particles.

Analysis of the various possible causes of obliteration leads to the conclusion that the change in the rate of flow of dispersed systems through narrow channels is due to a large number of physicochemical and hydrodynamic phenomena, ultimately amounting to the trapping of particles on the walls and their subsequent coagulation. The specific character of the dispersions with a time-dependent flow rate is primarily determined by the low resistance of the particles to adhesive forces, and secondly by the extremely low numerical concentration of the dispersed phase. The combination of these factors is one of the main conditions governing the blocking of capillary channels.

When present in a comparatively large volume, microscopic objects may exist in the suspended state for a long time. The position changes sharply if the suspensions are flowing in a volume, one of the dimensions of which is comparable with the mean displacement of the particles in the time t.



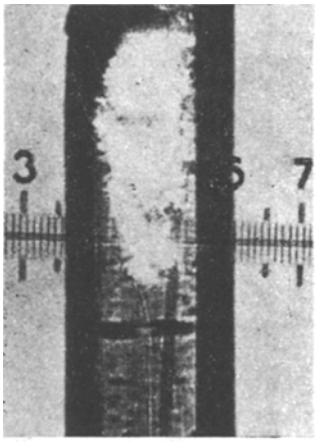


Fig. 3 Fig. 4

Fig. 3. Dependence of the volumetric (Q, cm^3/min) flow of the suspensions on the time of flow (t, min) for a pressure drop in the brass capillary of 1.55 kg/cm^2: 1)-3) graphite with a concentration of 0.01, 0.005, 0.0005 wt.% respectively; 4) quartz (0.0005 wt. %); 5) aluminum (0.0005 wt.%) in purified oil.

Fig. 4. Microscope photograph of the mouth of a glass capillary after obliteration with commercial oil MVP at $\partial p/\partial x = 8.5 \cdot 10^6$ N/m^3.

In the hydrodynamic flow of a Newtonian liquid, particles moving at different distances from the axis of the channel have different forward velocities, and may rotate around their own centers of inertia. It has been shown [8] that neither of these factors can produce any substantial interaction between spherical objects in a laminar flow; near the axis particles may collide simply as a result of their Brownian motion.

It was later concluded [9] when studying the behavior of dispersions in a flow that collisions between the particles were considerably intensified by turbulent diffusion appearing in the presence of a velocity gradient in the boundary layer. Still earlier [10] allowance was made for the effects of molecular diffusion and the velocity gradient of the dispersion medium on the coagulation process:

$$-\frac{dn}{ndt} = \left\{\frac{4kT}{3\eta} + \frac{r^3}{6}\left|\frac{\partial u}{\partial r}\right|\right\} n. \tag{1}$$

For a cylindrical channel we have [9]

$$\left|\frac{\partial u}{\partial r}\right| = \frac{R}{2\eta}\left|\frac{\partial p}{\partial x}\right|. \tag{2}$$

Substitution of (2) into (1) gives

$$-\frac{\partial n}{ndt} = \left\{\frac{4kT}{3\eta} + \frac{r^3 R}{12\eta}\left|\frac{\partial p}{\partial x}\right|\right\} n. \tag{3}$$

Taking $kT = 4.2 \cdot 10^{-21}$ J, $\eta = 0.02$ N·sec/m^2, $n = 10^{12}$ $1/m^3$, $r = 1 \cdot 10^{-6}$ m, $R = 5 \cdot 10^{-5}$ m, and $\partial p/\partial x = 15.3 \cdot 10^7$ N/m^3 we obtain

$$-\frac{dn}{ndt} = (2.8 \cdot 10^{-7} + 0.3 \cdot 10^{-1})\ 1/\text{sec}.$$

Thus coagulation associated with the velocity gradient in a boundary layer is much greater than that associated with the Brownian motion of the particles. With increasing dp/dx the velocity gradient becomes greater, in agreement with the earlier-mentioned increase in the intensity of obliteration with pressure. In addition to the collision and adhesion of the particles, these may also become detached. Calculations

show that, in the flow of commercial oils and suspensions only a small part of the volume of the dispersed phase is detained in the capillary channel (0.1-1.0 vol.%), forming a high-strength structure. The greater blocking of the channels in the end regions is evidently associated with the rise in velocity gradient at these points. The outflow is greatly stabilized (Fig. 2, curve 5) when the mouth of the capillary is enlarged to 125μ and given the form of a funnel.

The factor of ion–electrostatic interaction does not apparently play any major part in the obliteration of a channel when there is no electric field in the gap.

Obliteration during the flow of emulsions deserves special attention. This problem requires a detailed examination, but there is a certain opinion [11] to the effect that dispersed liquid particles behave in the same way as solids.

Summarizing all the foregoing, we may say that, for a number of technological systems (hydraulic drives and automatic equipment), existing methods of eliminating the obliteration of gaps [3, 4] should be supplemented by a more reasonable choice of channel shape and also the careful removal of dispersed solid and liquid impurities.

NOTATION

Q	volumetric rate of flow;
t	time of flow;
n	number of particles in unit volume;
k	Boltzmann's constant;
T	absolute temperature
η	dynamic viscosity of the medium;
r	radius of the particle;
R	radius of the capillary;
$\partial u/\partial r$	velocity gradient in the direction of the radius;
$\partial p/\partial x$	pressure gradient in the capillary.

LITERATURE CITED

1. R. E. Wilson and D. P. Barnard, Ind. Eng. Chem., 14, 692 (1922).
2. A. S. Akhmatov, Dokl. Akad. Nauk SSSR, 30, 119 (1941).
3. A. G. Shashkov, Author's Abstract of Candidate's Dissertation, Inst. Avtom. i Telemekh., Moscow (1955).
4. I. N. Kichin, Avtomatika i Telemekhanika, 18, No. 8 (1957).
5. A. S. Akhmatov, Molecular Physics of Boundary Friction [in Russian], Fizmatgiz, Moscow (1963).
6. N. N. Krasikov, Khimiya i Tekhnol. Topliv i Masel, No. 6 (1970).
7. M. E. Balashov, Izmeritel'. Tekh., No. 3 (1970).
8. G. R. Kirchhoff, Mechanics [Russian translation], Izd. AN SSSR, Moscow (1962).
9. E. Richardson, Dynamics of Real Liquids [Russian translation], Mir, Moscow (1965).
10. M. Schmolukowski, J. Phys. Chem., 92, 129 (1917).
11. V. Vand, J. Phys. Chem., 52, 314 (1948).