RHEOLOGICAL EFFECT IN THE FILTRATION OF DISPERSE SYSTEMS

N. V. Stepanov

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An experimental and theoretical study is made of the effect of the viscoelastic properties of disperse systems on their filtration rate.

In the filtration of disperse systems, rate anomalies connected with the properties of the systems are observed. Experimental attempts to describe these anomalies [1-3] did not touch on the nature of the phenomena and thus do not permit their prediction. A comparison made in [4] of the filtration of clayey suspensions through plane and radial bag filters showed that the rate of filtration through a crust deposited on a flat horizontal surface was roughly half the rate through the annular lateral surface. Meanwhile, in most cases, the clayey crust was thicker for linear filtration. This result conflicts with the material balance of the deposition process. The form of the filtering surface also had an effect on the results.

To study the effect of the form of the filtering surface, we used three different surfaces of the same area: from the end of a filter press having the form of a cylinder, and from the sides in the form of a ring and half-ring. We filtered suspensions containing 6 and 8 wt. % Sarigyukhsk bentonite. A pressure drop of 0.25 MPa was created above by compressed gas. In filtering from the end and through the half-ring, the differences between the discharge of the filtrate and the thickness of the crust (cake) were no greater than the measurement errors. At the same time, in radial filtration through the annular surface, the discharge of filtrate was nearly twice as great and cake thickness was much smaller than in the two other cases examined.

We will explore the reasons for these anomalies. In filtration through an annular filter, the change in the volume of the suspension causes it to move relative to the cake that is being deposited on the surface of the filter. As is known, the motion of suspensions in impermeable [5] and permeable [6, 7] tubular channels is characterized by a wall effect associated with a viscosity anomaly for the boundary layer and a reduction in friction. One of the existing hypotheses concerning the viscosity anomaly involves a reduced content of the disperse phase in this layer [8], while another hypothesis reflective of the results of recent studies in this region involves the slip of layers of particles surrounded by bound water relative to each other [9, 10]. Thus, the structure of the suspension undergoes preliminary disintegration and the freeing of liquid phase from the suspension occurs directly on the surface of the cake rather than in its pores.

Such quasistatic radial filtration occurs when the suspension moves perpendicular to the filtration flow, and it takes place over the entire perimeter of the filtering surface. This even creates a "body" of the suspension all sides of which are in contact with the filtering surface. Henceforth, by radial filtration we will mean this type of quasistatic filtration.

The separation of the liquid and solid phases occurs differently in linear filtration, when the direction of motion of the suspension coincides with the direction of the filtration flow. Suspension deformed by a certain amount $\varepsilon$ is pressed into the pores of the cake, the amount of deformation being approximately proportional to the applied load $\sigma$ [11]. This deformation develops until the load exceeds a certain critical value $\sigma_0$ at which the shear stresses $\tau \geq \tau_0$. In contrast to the flow of one-phase viscoplastic fluids in pore channels, after $\sigma_0$ is exceeded the suspension undergoes a phase transformation into filtrate and solid deposit. The pressure gradient in the cake causes the liquid phase to be drawn into it, while the solid phase is deposited on its surface.

The limiting strain $\varepsilon_0$ of the suspension at which it breaks up in the pore channels depends on the applied load $\sigma_0$, the dynamic shear stress $\tau_0$ of the suspension, and the diam-

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TABLE 1. Initial Pressure Gradient in the Filtration of a Suspension $\frac{\Delta P_0}{\Delta P_0/\Delta P}$, MPa

| Number of suspension | $\tau_0$, dPa | $\eta$, mPa·sec | Cake formation pressure ΔP, MPa: 0,25 | | | 0,5 | | | 5,0 |
|---|---|---|---|---|---|---|---|---|---|
| | | | Cake formation time, min: 5 | 10 | 15 | 5 | 10 | 15 | 15 |
| 1 | 6,7 | 2,2 | $\frac{0,03}{0,12}$ | $\frac{0,03}{0,12}$ | $\frac{0,04}{0,16}$ | $\frac{0,05}{0,10}$ | $\frac{0,06}{0,12}$ | $\frac{0,06}{0,12}$ | $\frac{0,52}{0,104}$ |
| 2 | 23,0 | 4,8 | $\frac{0,07}{0\ 28}$ | $\frac{0,08}{0,32}$ | $\frac{0,09}{0,36}$ | $\frac{0,10}{0,20}$ | $\frac{0,11}{0,22}$ | $\frac{0,11}{0,22}$ | $\frac{1,10}{0,22}$ |

TABLE 2. Properties of the Investigated Disperse Systems

| Type and composition | Serial number | Concentration of solid phase, % | $\tau_0$, dPa | $\eta$, MPa·sec | Permeability of cake $k \cdot 10^{-3}$, $\mu m^2$ | Velocity losses $\bar{v}_0 \cdot 10^{-3}$, cm/sec |
|---|---|---|---|---|---|---|
| Suspension of Sarigyukhsk bentonite | 1 | 4 | 4,0 | 1,5 | 0,022 | 0,21 |
| | 2 | 5 | 6,5 | 2,0 | 0,025 | 0,22 |
| | 3 | 6 | 3,2 | 2,2 | 0,017 | 0,07 |
| | 4 | 8 | 22,7 | 4,4 | 0,026 | 0,34 |
| | 5 | 9 | 37,3 | 5,4 | 0,017 | 0,37 |
| | 6 | 10 | 61,4 | 6,4 | 0,021 | 0,58 |
| | 7 | 12 | 167,0 | 10,8 | 0,029 | 1,6 |
| Suspension of Druzhkovsk clay | 8 | 21 | 17,3 | 1,5 | 0,18 | 0,62 |
| | 9 | 28 | 27,0 | 3,0 | 0,16 | 0,44 |
| | 10 | 30 | 57,2 | 4,1 | 0,15 | 0,68 |
| | 11 | 40 | 112,0 | 4,9 | 0,13 | 1,03 |
| | 12 | 43 | 184,0 | 8,2 | 0,18 | 1,21 |
| Emulsion of bentonite, 12% petroleum, and 0.2% sulfanilyl | 13 | 9 | 185,0 | 12,5 | 0,013 | 0,14 |

eter of the channels and is proportional to $\sqrt{k}$. We will study this relationship by means of dimensional theory:

$$f\left(\frac{\sigma_0}{\varepsilon_0}, \sqrt{k}, \tau_0\right) = 0.$$

In accordance with the π-theorem, the number of dimensionless parameters is equal to unity. It follows from this that

$$\pi_1 = \left(\frac{\sigma_0}{\varepsilon_0}\right)^1 \sqrt{k}\, \tau_0^{-1},$$

or

$$\sigma_0 = \frac{\alpha \varepsilon_0 \tau_0}{\sqrt{k}}. \tag{1}$$

Equation (1) is analogous to the equation presented in [12] for the filtration of viscoplastic fluids, where $\sigma_0$ and $\varepsilon_0$ correspond to the initial gradient $\Delta P_0$ and the length of the filtration channels $\ell$, while $\alpha = 1.68 \cdot 10^{-2}$.

The dynamic shear stress $\tau_0$ of the suspension is relatively large, while the permeability of the cake k is very low. Thus, despite the small value of $\varepsilon_0$, the limiting stress for breakup of the suspension $\sigma_0$ may reach considerable values.

To measure the breakdown stress of the suspension or the initial pressure gradient $\Delta P_0$, we used 5 and 8% suspensions of Sarigyukhsk bentonite (Nos. 1 and 2 in Table 1, respectively). Filtering of these suspensions under pressures of 0.25, 0.5, and 5 MPa initially produced a clayey cake of known thickness. We then gradually increased the pressure until filtration began again. The pressure at which this took place $\Delta P_0$ was measured.

Similar experiments were conducted for radial filtration. After the pressure was relieved, suspension No. 1 continued to undergo filtration at a lower rate due to the pressure of its column, i.e., there was almost no initial pressure gradient in this case. For suspension No. 2, the initial pressure gradient was more than an order less than the gradient obtained with linear filtration and was henceforth ignored.

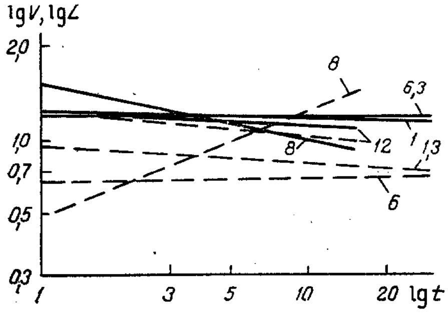


Fig. 1. Time change in the ratios of filtration velocities V (solid lines) and cake thicknesses L (dashed lines) obtained in radial and linear filtration (the enumeration of the suspensions in Figs. 1-3 corresponds to Table 2). log t, min.

We used several suspensions (Table 2) to study the effect of rheological properties. For these suspensions, we measured the volume of filtrate V and the thickness of the cake L over time with linear and radial filtration. Figure 1 shows the change in V and L for certain of the suspensions shown in Table 2. As is known [1], the change in the volume of filtrate over time is approximated by power functions whose differentiation can yield the velocity of the filtrate.

The volume of filtration accumulated and its velocity in radial filtration was 1.5 times greater than for linear filtration for all of the suspensions (Table 2). Here, the thickness of the cake for the bentonite suspension was much smaller in radial filtration than in linear filtration. However, the thickness for the suspension of Druzhkovsk clay was several times greater in the radial case than the linear case. It should be noted that the experiments with the suspensions were begun one day after they were prepared, except for suspensions No. 3 (Table 2). This suspension was filtered 1 h after it was prepared. In this case, the change in the rheological properties of the suspension with an increase in the concentration of the solid phase deviated from the general law, and we were able to distinguish their effects on filtration.

The calculations showed that the ratio of the total volume of filtrate and moisture in the cake to the volume of the solid phase in the skin exceeds the theoretical values for radial filtration. This can be attributed to erosion of the cake by the downward-moving suspension or the excess dispersion medium in the boundary layer. The largest deviations of these ratios are seen during the first several minutes of filtration, when the gradient of the velocity of the suspension is relatively large. Analysis of the empirical data showed that, with a confidence level of 0.9, the rate of erosion of the cake depends linearly on the gradient of suspension velocity. The empirical correlation coefficient is $5.3 \cdot 10^{-4}$ for bentonite and $1.8 \cdot 10^{-3}$ cm for Druzhkovsk clay.

In the case of linear filtration of suspensions with the deposition of a clayey cake, we are dealing with two different systems. One of these systems (the suspension) is broken down in the pores of the cake, while the other is filtered through it. Thus, the applied pressure gradient $\Delta P$ is distributed between the clay-bearing cake $\Delta P_1$ and a certain thickness of the layer of suspension being broken down $\sigma_0$:

$$\Delta P = \Delta P_1 + \sigma_0. \tag{2}$$

Since the pressure gradient $\Delta P_1$ increases over time with an increase in the thickness of the cake, in the case of a constant applied pressure gradient $\Delta P$ the limiting stress for the suspension $\sigma_0$ — which is basically the pressure loss due to the rheological resistance of the suspension — should decrease over time. Thus, $\Delta P_1$ and $\sigma_0$ are in complex dynamic equilibrium during filtration. This equilibrium depends on the hydrodynamic properties of the clayey cake and the rheological properties of the suspension.

Since resistance is almost no factor in radial filtration and the entire pressure gradient acts on the clayey cake, by knowing the filtration rate and cake thickness we can calculate the permeability k of the cake [13]. This quantity is completely or almost completely

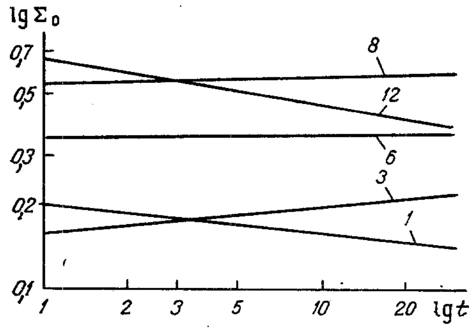


Fig. 2

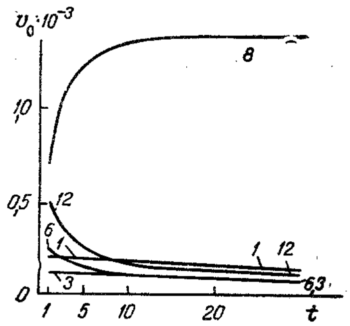


Fig. 3

Fig. 2. Time change in the dimensionless load parameter $Z_0$ corresponding to the breakdown of a disperse system in the pores of the filter cake during linear filtration.

Fig. 3. Time change in the loss of filtrate velocity $v_0$, cm/sec, during linear filtration. t, min.

independent of time, so we will henceforth use its mean values $\bar{k}$ (Table 2). If we assume that the permeabilities of a cake for linear and radial filtration are the same for identical suspensions, then with a known filtration rate and cake thickness in the case of linear filtration we can use Darcy's law to evaluate the pressure drop $\Delta P_1$ on the cake. We can use Eq. (2) to find the stress $\sigma_0$. The quantity $\Sigma_0 = \sigma_0/\Delta P$ (Fig. 2) is considerably greater than the ratio $\Delta P_0/\Delta P$ (Table 1). These differences can be attributed to the fact that when we conducted the experiment (Table 1), we fixed the value $\Delta P_0$ corresponding to the beginning of filtration. Meanwhile, the values of $\sigma_0$ were obtained at considerably greater filtration rates v. The relative quantity $\Sigma_0$ reaches 0.15-0.7 ($\Delta P$). An increase in the applied external pressure $\sigma_0$ is accompanied by an increase in $\Delta P_0$ (Table 1), since the permeability of the cake and, thus, the diameter of the channels are reduced.

Redistribution of the applied pressure gradient $\Delta P$ between the clayey cake and the suspension leads to a decrease in the rate of linear filtration v. It is equal to the difference between the theoretically possible filtration rate $v_1$ in radial filtration and the velocity losses $v_0$ due to the rheological resistance of the suspension:

$$v = v_1 - v_0. \tag{3}$$

We can proceed from here to determine the velocity losses $v_0$. Figure 3 shows the time change in $v_0$, which stabilizes after 15-20 min.

To obtain the dependence of the mean loss of filtration rate $\bar{v}_0$ on the parameters $\sigma_0$, $\eta$, $\varepsilon_0$, and k, we make use of dimensional theory

$$\pi_2 = \left(\frac{\sigma_0}{\varepsilon_0}\right)^1 \eta^{-1} \left(\frac{v_0}{k}\right)^{-1},$$

or

$$\bar{v}_0 = \beta \frac{k}{\eta} \frac{\sigma_0}{\varepsilon_0}. \tag{4}$$

Inserting $\sigma_0$ from (1) into (4), we obtain a result similar to that found in [12]

$$\bar{v}_0 = \gamma \frac{\sqrt{k}\,\tau_0}{\eta}, \tag{5}$$

where $\gamma = \alpha\beta$.

Values of the coefficient $\gamma$ can be obtained by comparing experimental $\bar{v}_0$ and theoretical $v_0$ values of the velocity loss. For a bentonite suspension in the concentration range 4-10%, $\gamma = 1.7 \cdot 10^{-2}$. Since $\gamma$ is equal to the value of $\alpha$ obtained in [12] for viscoplastic fluids, $\beta = 1$. The change in $\gamma$ for a 12% bentonite suspension is apparently due to the fact that it has a gel-like structure. The value of the coefficient $\gamma$ also depends on the physicochemical properties of the disperse system undergoing breakdown. For Druzhkovsk clay, $\gamma = 0.4 \cdot 10^{-2}$.

Using the values obtained for $\gamma$ and $\alpha$, we can estimate the depth of "penetration" $\varepsilon_0$ of the bentonite suspension into the pores of the cake in linear filtration. This depth decreases from 0.04 to 0.003 cm with an increase in the concentration of the solid phase.

The filtration of emulsions may also be accompanied by losses of pressure and velocity. Thus, emulsion No. 13 (Table 2) had an empirical velocity loss $v_0 = 0.14 \cdot 10^{-3}$ cm/sec. With a rate of linear filtration $v = 0.16 \cdot 10^{-3}$ cm/sec and a cake thickness of 1 mm, $\Sigma_0 = 0.48$ and $\gamma = 0.26 \cdot 10^{-2}$.

The equation of the kinetics of linear filtration follows from (3-5) and Darcy's law

$$v = k\left(\frac{\Delta P_1}{\mu l} - \beta\frac{\sigma_0}{\eta\varepsilon_0}\right) = \frac{k\Delta P_1}{\mu l} - \gamma\frac{\sqrt{k}\,\tau_0}{\eta}.$$

Rheology can influence the contamination of productive beds during drilling, the operation of equipment in commercial filtration processes, and the results of experiments on the filtration of disperse systems.

## NOTATION

k, permeability of the filter cake; $\ell$, cake thickness in linear filtration; L, ratio of cake thicknesses in radial and linear filtration; $\Delta P_1$, hydrodynamic pressure drop on the calyey cake; $\Delta P_0$, initial pressure drop; $\Delta P$, applied pressure gradient; $\bar{v}_0$ and $v_0$, calculated and empirical values of loss of filtrate velocity during linear filtration; v, $v_1$, experimental rates of linear and radial filtration; $V = v_1/v$; $\alpha$, $\beta$, $\gamma$, dimensionless empirical coefficients; $\varepsilon_0$, depth of penetration of suspension into pores of cake; $\eta$, plastic viscosity of suspension; $\mu$, dynamic viscosity of filtrate; $\sigma_0$, dimensionless load corresponding to breakdown of the disperse system; $\Sigma_0 = \sigma_0/\Delta P$; $\tau_0$, dynamic shear stress of the suspension.

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