Journal of Engineering Physics and Thermophysics, Vol. 66, No. 5, 1994

JUSTIFICATION OF RHEOTECHNOLOGICAL METHODS OF CONTROL OF COLMATAGE

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UDC 539.30+622.244+517.9

Theoretical and experimental investigations of localized structures appearing in filtration of nonlinear viscoplastic drilling fluids are reported. The depth of penetration of mud into a porous medium is shown to be dependent on the rate of change of the pressure on the boundary. This fact has been suggested for use in creation of colmatage barriers that prevent penetration of drilling mud into strata.

Introduction. Penetration of drilling fluids into a stratum (upon its opening) and their filtration can result in a sharp reduction in the stratum permeability due to colmatage processes (cluttering of the pores with disperse particles suspended in the fluid). Investigations show that this phenomenon serves as a basic cause of reduction in well output. Sometimes, due to colmatage, well output is reduced by tens of times. Colmatage taking place in close vicinity to a well can play a positive role as well, since it leads to formation of a low-permeability layer of the porous medium that limits penetration of drilling mud into the stratum. This effect can be purposefully employed to protect the near-bottom zone when technological techniques enabling the creation of colmatage barriers of sufficiently small thickness near the well walls are available.

In the present paper it is shown that rheotechnological methods can be used to control colmatage processes. These methods are based on the use of specific features of the rheology of drilling mud (the structural viscosity of the fluids is strongly dependent on their shear rate [1-4]). An analysis of certain exact solutions of filtration equations for a nonlinear viscoplastic fluid is performed. On the basis of the analysis it is shown that the intrusion depth of the fluid into a stratum can be regulated by controlling the rate of pressure change at the porous medium boundary. Experimental results on investigation of filtration of water-polymer drilling fluids in a laboratory model of a stratum are given that confirm qualitative conclusions made in an analysis of mathematical models.

Localization of Boundary Regimes. The rheology of drilling fluids is determined by the interaction of molecules and supramolecular aggregates that tend to form a spatial structure, which provides the fluids with viscoplastic properties. Viscoplasticity means that the fluids start to move only when the absolute value of the pressure gradient exceeds a certain critical value (the starting pressure gradient). In movement the behavior of the structured fluid also differs substantially from the behavior of an ordinary viscous (Newtonian) fluid, since an increase in the shear rate leads to further degradation of the structure. Therefore, drilling fluids should be included in the class of nonlinear viscoplastic media whose structural viscosity depends on the velocity of movement.

Equations describing the transient radially symmetric filtration of a nonlinear viscoplastic medium are of the form [5, 6]:

$$m\beta \frac{\partial P}{\partial t} = -\frac{1}{x^s}\frac{\partial}{\partial x}(x^s v):\ x \in (x_1,\ +\infty),\quad t \in (0,\ +\infty); \tag{1}$$

$$v = \begin{cases} -\dfrac{k}{\mu(|v|)} Z \operatorname{sgn}\left(\dfrac{\partial P}{\partial x}\right), & Z > 0, \\ 0, \quad Z \le 0, \end{cases} \tag{2}$$

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Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 66, No. 5, pp. 573-579, May, 1994. Original article submitted April 22, 1992.

1062-0125/94/6605-0508$12.50 ©1995 Plenum Publishing Corporation

where m, β, and k are the porosity, compressibility, and permeability of the porous medium; P is the pressure; $\mu = \mu(|v|)$ is the fluid viscosity, which depends on the filtration rate v:

$$Z = \left|\frac{\partial P}{\partial x}\right| - \Theta$$

(Θ is the initial pressure gradient; $S = 0$, 1, or 2 for flat, flat-radial, and spherical filtration, respectively). If we restrict ourselves to consideration of solutions monotonical decreasing in x and replace the variables by the dimensionless ones

$$\bar{P} = P/P_0, \quad \bar{\Theta} = \Theta/\Theta_0, \quad Z = Z/\Theta_0, \quad \bar{v} = v/v_0,$$

$$\bar{\mu}_1(\bar{v}) = \mu(v_0\bar{v})/\mu_0, \quad \bar{t} = t/t_0, \quad \bar{x} = \frac{x}{x_0},$$

where P_0, Θ_0, and μ_0 are certain characteristic values of the pressure, initial pressure gradient, and viscosity;

$$l_0 = P_0/\Theta_0; \quad v_0 = \frac{k}{\mu_0}\Theta_0; \quad t_0 = x_0^2/a;$$

$a = k/m\beta\mu_0$ is the piezoconductivity coefficient, then by differentiating with respect to x we obtain from (1) the equation

$$\frac{\partial\bar{Z}}{\partial\bar{t}} + \frac{\partial\bar{\Theta}}{\partial\bar{t}} = \frac{\partial}{\partial\bar{x}}\left[\frac{1}{\bar{x}^s}\frac{\partial}{\partial\bar{x}}(\bar{x}^s\Phi(\bar{Z}))\right], \quad \bar{x}\in R, \quad \bar{t}\in(0; +\infty), \tag{3}$$

where R is the domain in which $Z > 0$; $\bar{v} = \Phi(\bar{Z})$ is the function inverse to the function $\bar{Z} = \bar{v}\mu_1(\bar{v})$. We will consider that the function $\Phi(Z)$ is a monotonically increasing one, and

$$\Phi'(0) = 0. \tag{4}$$

Hereinafter, we will use only dimensionless quantities, and therefore the bars will be omitted.

First of all we consider solutions of (3) corresponding to a constant Θ: $\Theta = \Theta_1$. By virtue of (4) Eq. (3) is degenerate: at $Z = 0$ the condition of its parabolicity is violated. As is known [7, 8], such equations can have generalized solutions describing propagation of disturbances with a finite penetration depth (as mentioned above, precisely these solutions are of interest to us). In order to study the behavior of localized regimes in more detail, we approximate the function by a power dependence

$$\Phi(Z) = Z^\lambda, \quad \lambda = \text{const} > 1.$$

By making the replacement

$$u = x^{s/\lambda}Z, \quad y = x^\sigma, \quad \tau = \sigma^2 t,$$

we obtain from (3) (for $\Theta = \text{const}$)

$$\frac{\partial u}{\partial\tau} = y^\alpha\frac{\partial}{\partial y}\left(\frac{1}{y^\alpha}\frac{\partial u^\lambda}{\partial y}\right), \tag{5}$$

where

$$\sigma = 1 + \frac{S}{2}\left(\frac{\lambda - 1}{\lambda}\right), \quad d = \frac{S}{2\sigma\lambda}(\lambda + 1).$$

We consider a solution of (5) in the form of a running wave [7-9]:

$$u(\tau, y) = \begin{cases} T(\tau)\,[\xi^2(\tau) - y^2]^n, & y < \xi(\tau), \\ 0, & y \geq \xi(\tau). \end{cases} \tag{6}$$

Substituting (6) into (5), we obtain

$$\dot{T}(\xi^2 - y^2)^n + 2n\xi\dot{\xi}T(\xi^2 - y^2)^{n-1} = T^\lambda\,[4n\lambda(n\lambda - 1)\,y^2(\xi^2 - y^2)^{n\lambda-2} - \\ - 2(1-d)\,n\lambda(\xi^2 - y^2)^{n\lambda-1}], \tag{7}$$

where the dot denotes differentiation with respect to the time.

If we set $n = 1/(\lambda - 1)$ and assume that the function $\xi(\tau)$ satisfies the equation

$$\frac{1}{\xi}\frac{d\xi}{d\tau} = \frac{2\lambda}{\lambda - 1}T^{\lambda-1}, \tag{8}$$

we can cancel factors of the form $(\xi^2 - y^2)^n$ in (7) and obtain an equation relative to $T(\tau)$:

$$\frac{dT}{d\tau} = -B_0 T^\lambda, \tag{9}$$

where

$$B_0 = \frac{2\lambda}{\lambda - 1}\left(\frac{2}{\lambda - 1} + 1 - d\right).$$

From (9) and (8) we easily obtain

$$T = \frac{T_0}{(B\tau + 1)^{1/(\lambda-1)}}, \quad \xi = \xi_0(B\tau + 1)^\delta,$$

where $B = B_0(\lambda - 1)T_0^{\lambda-1}$, $T_0 = T(0)$, $\xi_0 = \xi(0)$, $\delta = 1/[2 + (\lambda - 1)(1 - d)] > 0$. This solution is a running wave with a front at the point $x = l(\tau) = \xi^{1/\sigma}(\tau)$. It is evident that $l(\tau) \to \infty$ as $\tau \to \infty$. The pressure distribution corresponding to this solution is determined by the expression

$$P(\tau, x) = \begin{cases} \Theta_1(l - x) + T(\tau)\int_x^l x^{-s/\lambda}\,[l^{2\sigma} - x^{2\sigma}]^n\,dx, \\ \qquad x_1 \leq x \leq l(t); \\ 0, \quad x > l(t). \end{cases} \tag{10}$$

In certain cases the integral in (10) may easily be taken. Thus, if $\lambda = 2$ and $S = 0$, then $n = 1$, $\sigma = 1$, $d = 0$. Here,

$$P(\tau, x) = \Theta_1(l - x) + T(\tau)\left[l^2(l - x) - \frac{1}{3}(l^3 - x^3)\right], \quad x_1 \leq x \leq l.$$

Setting $x_1 = 0$, we determine the change in the pressure at the boundary of the porous medium $P_1(\tau) = P(\tau, x_1)$:

$$P_1(\tau) = \xi_0\Theta_1(Bt + 1)^{1/3} + 2T_0\xi_0^3/3.$$

Thus, for $\Theta_1 \neq 0$ the solution obtained corresponds to unbounded growth of the pressure at the boundary (a regime with sharpening). On the other hand, if $\Theta_1 = 0$, then $P_1(\tau) \equiv 2T_0\xi_0^3 = \text{const}$.

From expression (10) it follows that at any moment of time drilling mud penetrates into the porous medium only to a limited depth. Therefore (when colmatage is "switched on"), the entire porous medium is not contaminated but only some near-boundary part of it. In order to define this qualitative approach more exactly, we consider a model in which degradation of the filtrational properties of the stratum due to colmatage processes is taken into account explicitly. We assume that precipitation of disperse particles of the drilling mud onto the pore walls results in an increase in the initial pressure gradient. It is known that in movement with high velocities the macromolecule globes can become "solid," which increases the rate of their precipitation [5]. Therefore, we may consider that the change in the quantity Θ is determined by the fluid movement velocity:

$$\frac{\partial\Theta}{\partial\tau} = \alpha_1 v^{\gamma} \quad \text{or} \quad \frac{\partial\Theta}{\partial\tau} = \alpha_1 Z^{\gamma\lambda} . \tag{11}$$

By analogy with the previous case we can obtain from (3) and (11) with $\gamma = 1/\lambda$ the following equation

$$\frac{\partial u}{\partial\tau} = y^2 \frac{\partial}{\partial y}\left(\frac{1}{y^{\alpha}} \frac{\partial u^{\lambda}}{\partial y}\right) - \alpha_1 u , \tag{12}$$

whose solution can again be sought in the form (6). Here, the functions $T(\tau)$, $\xi(\tau)$ and $\Theta(\tau, x)$ are determined by the equations

$$\frac{dT}{d\tau_1} = - T^{\lambda} - \alpha T , \tag{13}$$

$$\frac{d\xi}{d\tau_1} = b\xi T^{\lambda-1} , \tag{14}$$

$$\frac{\partial\Theta}{\partial\tau_1} = \begin{cases} \alpha T(\tau_1)\, x^{-S/\lambda} \left[\xi^2(\tau_1) - x^{2\sigma}\right]^n, & x \le l(\tau_1) , \\ 0 , \quad x > l(\tau_1) , \end{cases} \tag{15}$$

where $\tau_1 = B_0\tau$, $\alpha = \alpha_1/B_0$, $l = \xi^{1/\sigma}(\tau_1)$.

From (13) and (14) it follows that as $\tau_1 \to \infty$ the boundary of the localized domain $l(\tau_1)$ tends to the finite limit l_∞: $\ln l_{(\tau_1)} \approx \ln l_\infty - c \exp\left[-\alpha(\lambda - 1)_{\tau_1}\right]$, where c is a certain constant. Hence, the solution obtained corresponds to a standing wave. As an example, we consider again the particular case specified by the values $\lambda = 2$, $S = 0$, $x_1 = 0$. Then, $\sigma = 1$, $d = 0$, $B_0 = 12$. Assuming that $\Theta(0, x) \equiv 0$, we obtain

$$P(\tau_1, x) = F(\tau_1, x) + \alpha \int_{\tau_0(x)}^{\tau_1} F(\tau_1, x)\, d\tau_1 ,$$

where

$$F(\tau_1, x) = T(\tau_1)\left[l^2(l - x) - \frac{1}{3}(l^3 - x^3)\right] ,$$

$\tau_0 = \tau_0(x)$ is the function inverse to $l(\tau_0)$.

Figure 1b presents the function $P(\tau_1, x)$ at various times. The function was obtained by numerical integration of Eqs. (13)–(15) by the Runge-Kutta method with a step of $\Delta\tau = 0.02$ at $\alpha = 1$, $T_0 = 20$, $\xi = 0.1$. Curve 1 in this figure corresponds to a standing wave, and in Fig. 1a the boundary regime $P_1(\tau_1) = P(\tau_1, 0)$ is given.

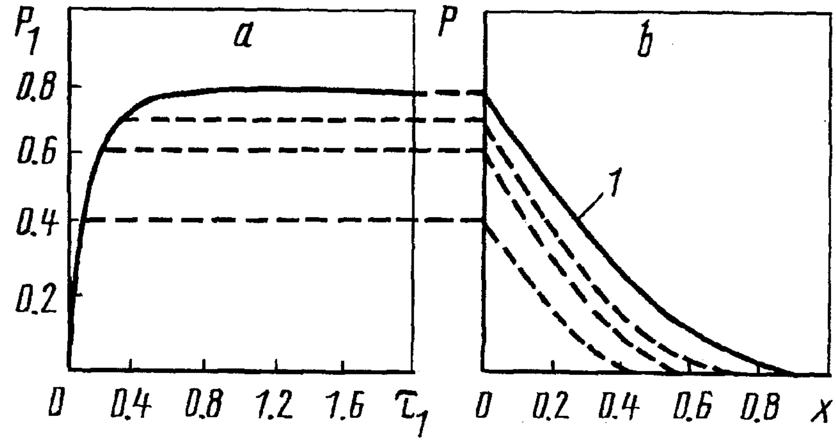

Fig. 1. Standing wave: a) the boundary regime $P_1(\tau_1) = P(\tau_1, 0)$; b) the function $P(\tau_1, 0)$ at various times.

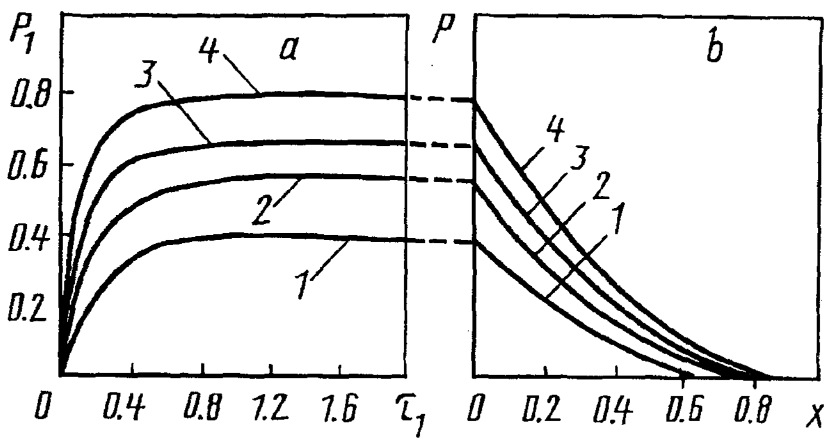

Fig. 2. Localized structures in various boundary regimes: 1) $T = 15$; $\xi_0 = 0.01$; 2) 20 and 0.005; 3) 20 and 0.05; 4) 20 and 0.1.

Figure 2b gives standing waves corresponding to various laws of pressure change at the boundary (Fig. 2a). From the form of these curves the important practical conclusion may be made that the higher the rate of change of the boundary pressure the more effective the produced colmatage barrier, i.e., the higher the pressure it can (at the same depth) withstand.

Experimental Investigation of Filtration of Water-Polymer Drilling Fluids. Investigations were performed on a special setup (Fig. 3) consisting of a measuring press, a high-pressure vessel, and a stratum model. The latter consists of three sections and three tubes coupled with each other (the length of each tube is 0.08 m). Thus, the length of the entire stratum model is 0.24 m. The stratum was simulated by thoroughly rammed quartz sand. The gas permeability of the stratum ranged from 0.5 to 1 μm^2. In 0.08 m intervals at the end of each section sample pressure gauges were fixed above, and drain valves were fixed below to sample the filtrate.

Experiments on the setup described were performed as follows. The high-pressure vessel was filled with a water-polymer solution. A 1% aqueous solution of K-4 polymer reagent was used as an experimental fluid. The solution in the vessel was pressurized to 4 MPa. Then the inlet valve to the strarun model was opened and the water-polymer solution started to penetrate into the stratum.

Experiments of two types were performed. In the former (Fig. 4a) the pressure at the inlet was raised from 0 to 4 MPa almost instantaneously and then maintained constant at 4 MPa up to the end of the experiment. In experiments of this type the outlet valve of the setup was closed. Readouts of each pressure gauge were written at equal time intervals. When the pressure changes rapidly at the front boundary of the stratum model layer the water-polymer solution starts to filter into the stratum. The pressure at gauge 2 in the first section starts to grow approximately 60 sec after the start of the disturbance. Pressure gauge 3 at the end of the second section started

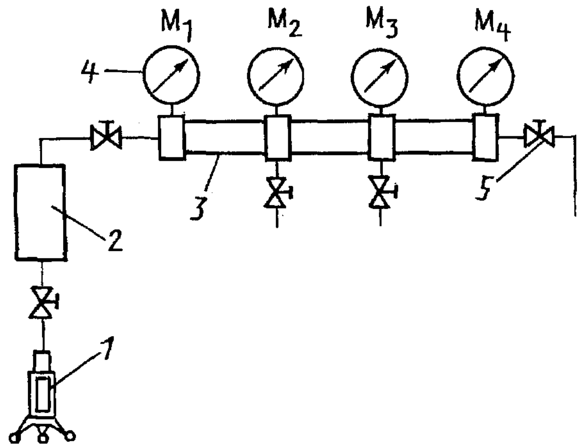

Fig. 3. Schematic diagram of the experimental setup: 1) the measuring press; 2) the high-pressure vessel with drilling mud; 3) the stratum model; 4) the sample pressure gauges; 5) the valves for sampling the filtrate.

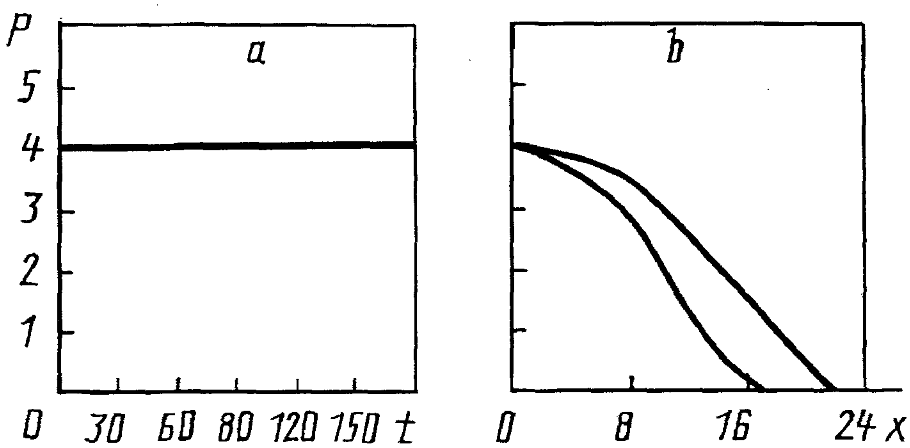

Fig. 4. Pressure distribution in the stratum model in filtration of a 1% aqueous solution of K-4 polymer when the pressure at the boundary was changed instantaneously. P_1, MPa; t, min; x, cm.

to detect a pressure change in 150 sec. Pressure gauge 4 at the end of the third section did not detect any changes in the pressure, i.e., the pressure was equal to zero. The above facts indicate that the front of polymer in the porous medium stopped between pressure gauges 3 and 4. Filtration of the water-polymer fluid was performed for 180 min. Readouts of the pressure gauges were plotted (Fig. 4b) to obtain a pressure distribution in the stratum model when the pressure at the boundary of the stratum changes rapidly.

The experiments showed that the pressure distribution stabilized 10 min after the start of filtration and did not change up to the end of the experiment. Here, the pressure gradient over the first section was higher than that over the second section. This picture probably occurs due to more effective sedimentation of the polymer particles in this section than in the first section of the model. Consequently, resistance to water-polymer fluid flow in this section is higher than that at the inlet to the model. In turn, in the third section the resistance to movement of the fluid became so high that the intrusion front stopped and localized at some distance from the end of the stratum model.

In the second type of experiment the pressure at the inlet was raised from 0 to 4 MPa slowly, in 10 min (Fig. 5). Here, a picture different from that in the previous experiment was observed. When the pressure at the inlet changes slowly, the fluid starts to filter into the stratum without significant resistance, and the front of the intrusion reaches the end of the stratum model in 10 min. The experiment was conducted for 180 min. In this time

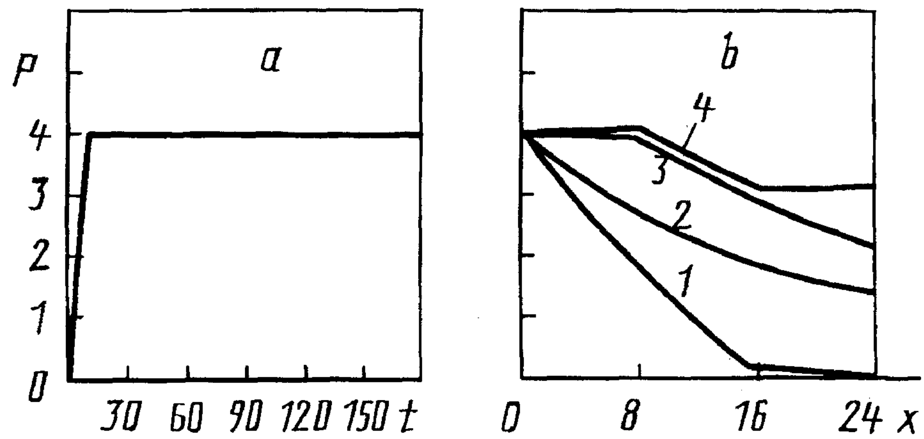

Fig. 5. Pressure distribution in the stratum model in filtration of a 1% aqueous solution of K-4 polymer when the pressure at the boundary was changed slowly: 1) 10 min; 2) 20; 3) 30; 4) 120.

the pressure at pressure gauge 2 in the first section of the model equalized to the initial level. Readouts of pressure gauges 3 and 4 were also substantially higher than those in the first type of experiment.

The experiments were repeated several times and showed the same behavior.

The experimental results obtained confirm that when a certain boundary regimes of pressure change are maintained a small depth of penetration of the fluid into the stratum can be provided. It has been shown that an increase in the rate of pressure change at the boundary of a porous medium results in a reduction in the depth of penetration of the fluid. This fact is suggested for use in the development of technological measures for preventing contamination of a stratum by drilling fluids.

Conclusion. Self-similar solutions of equations describing filtration of nonlinear viscoplastic fluids have been obtained in the present work. On the basis of their analysis the possibility of formation of localized structures has been shown whose depth of penetration into the porous medium depends on the rate of pressure change at the boundary of the stratum. In order to confirm this conclusion, an experimental investigation of filtration of polymer solutions used in drilling has been performed. This fact is suggested for use in the development of technological measures for preventing contamination of strata by drilling fluids.

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