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Research Paper

Study on Reservoir Damage Mechanism and Prediction of Damage Parameters

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Abstract: *The parameters of formation damage during drilling are the main factors that affect production capacity.According to the mud cake sedimentation and conservation equation, erosion equation, Darcy equation, the prediction model of drilling pollution parameters are established, and the amount of drilling fluid invasion anddistribution of invading fluidconcentration are predicted, thus providing theoretical basis for the parameters prediction of drilling damage.*
Keywords: *Drilling fluid, Formation damage, Filtrate invasion,Solid particles*

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I. INTRODUCTION

In the process of drilling, the invasion of drilling fluid to the formation will cause the formationaround wellbore polluted, and increase production differential pressure, meanwhile, reducethe well productivity [1].Formation damage during drilling is mainly due to solid particles invasion and filtrate invasion.The intrusion of solid particles will reduce pore radius of the hydrocarbon zone, and even block pore throats, thereby reducing the permeability of the formation[2-3].While filtrate invasion will cause acid sensitivity, water sensitivity, salt sensitivity and other sensitive formation damage, which will also result in the decline of formation permeability. Therefore, it is particularly important to establish the prediction model of formation damage parameters during drilling.

II. PREDICTION MODEL OF DRILLING FLUID INVASION

The solid particle invasion into formation is relatively shallow, generally within the range of a few centimeters near the wellbore; the fluid invasion is relatively deep, usually rangingfrom dozen centimeters to tens of centimeters[4].Therefore, drilling fluid invasion is the main reason for the decrease of permeability around the wellbore. We assume the drilling fluid system is water-based, single-phase radial flow, isothermal flow, constant bottomhole pressure, constantformation pressure, no solid particles invading , constant porosity and absolute permeabilityof invaded zone, and assuming the solidprecipitates near the borehole wall and forms mud cake, so the thickness of mud cake is primarily a function of the concentration of the drilling fluid,and the quality of solid particles which form the mud cake can be expressed as:

$$m_c = A_c x_c (1-\phi_c)\rho_c \quad (1)$$

Where: ρ_c — the cake density, g/cm^3 ; ϕ_c — the cake porosity, dimensionless; x_c — the cake thickness, cm ; m_c — the quality of solid particles in mud cake, g ; A_c — the area of mud cake, cm^2.

In the process of drilling circulation, the drilling fluid invasion is a dynamic process. The increase velocity of mud cake thickness is the difference between settling velocity and erosion velocity of the mud cake, and the settling velocity is a function of the amount of intrusion fluid, the erosion velocity is a function of shear force of drilling fluid along the borehole[5].With the increase of the thickness of the cake, the setting velocity becomes slower, while the erosion rate becomes fasteruntil the setting rate and the erosion rate reach equilibrium. The mud cake quality conservation equation can be expressed as:

Theincrease velocity of cake quality=the settling velocity-the erosion velocity (2)

The settling velocity of mud cake is proportional to the mass flow of solid particles in drilling fluid:

$$d_c = A_c u_{in} C_{solid} \quad (3)$$

The erosion velocity of mud cake is related with shear stress:

$$e_c = k_\tau A_c \tau \tag{4}$$

where: d_c — the settling velocity of cake, g/s; u_{in} —the intrusion velocity of drilling fluid along the borehole wall, cm/s; C_{solid} — the solid particle concentration in drilling fluid, g/cm^3; e_c — the erosion velocity of cake, g/s; k_τ — erosion coefficient, 1/s; τ — shear stress of mud circulation, g/cm^2.

Combining equation 3 and 4, and substituting this into equation 2,the increase velocity equation of mud cake thickness is:

$$\frac{dm_c}{dt} = A_c u_{in} C_{solid} - k_\tau A_c \tau \tag{5}$$

The increase velocity of mud cake thickness can also be expressed in differential form as equation (3-1):

$$\frac{dm_c}{dt} = A_c \frac{dx_c}{dt}(1-\phi_c)\rho_c \tag{6}$$

Combine equation 5 and 6, the increase velocityequation of cake thickness is:

$$\frac{dx_c}{dt} = \frac{u_{in} C_{solid} - k_\tau \tau}{(1-\phi_c)\rho_c} \tag{7}$$

$$u_{in} = \frac{q_{in}}{2\pi r_c \Delta L} \tag{8}$$

The thickness of mud cake can be expressed as:

$$x_c(t) = r_w - r_c(t) \tag{9}$$

Where: x_c —The thickness of mud cake, cm; t — time, s; ϕ_c — the cake porosity, dimensionless; ρ_c — the cake density, g/cm^3; q_{in} — the intrusion flowing of drilling fluid along the borehole wall, cm^3/s; ΔL —well length, cm; r_c — the radius of the inner wall of mud cake, cm; r_w — the borehole radius, cm.
Substitute equation 8 into equation 7 and integrate it as:

$$\frac{\partial x_c}{\partial t} = a q_{in}(t) + b \tag{10}$$

$$a = \frac{1}{2}\frac{C_{solid}}{\rho_c(1-\phi_c)\pi r_c \Delta L} \quad b = -\frac{k_\tau \tau}{\rho_c(1-\phi_c)}$$

The increase velocity of mud cake thickness is affected by the amount of drilling fluid invasion,so in order to solve the thickness of mud cake, the amount of drilling fluid invasion must be determined, according to the Darcy law:

$$\frac{\partial p}{\partial r} = -\frac{u\mu}{k} \tag{11}$$

For equation11,upper limit: $p_w \cdots p_e$, $r_w \cdots r_e$ integrating, when $t = 0$, $x_c = 0$:

$$p_w - p_e = \frac{1}{2}\frac{q_{in}(0)\mu \ln \frac{r_e}{r_w}}{\pi \Delta L K} \tag{12}$$

For equation11, upper limit: $p_w \cdots p_e$, $r_w(x_c > 0) \cdots r_e$ integrating, when $t = t$, $x_c = x_c(t)$:

$$p_w - p_e = \frac{1}{2}\frac{q_{in}(t)\mu\left(\ln\frac{r_e}{r_w} + \frac{K\ln\left(\frac{r_w}{r_w - x_c(t)}\right)}{K_c}\right)}{\pi \Delta L K} \tag{13}$$

Where: p_{w} — borehole pressure, $10^{-1}\mathrm{MPa}$; p_{e} — pore pressure, $10^{-1}\mathrm{MPa}$; K —the original formation permeability, $\mu\mathrm{m}^2$; K_{c} —mud cake permeability, $\mu\mathrm{m}^2$; μ —invading fluid viscosity, $\mathrm{mPa.s}$; r_{e} —invaded zone outer radius, cm; $q_{\mathrm{in}}(0)$ —intrusion volume of initial time, cm^3/s; $q_{\mathrm{in}}(t)$ — intrusion volume, cm^3/s.

Combine equation 12 and 13, thevolume of intrusion fluid can be expressed as:

$$q_{\mathrm{in}}(t)=\frac{q_{\mathrm{in}}(0)\ln\left(\frac{r_{\mathrm{e}}}{r_{\mathrm{w}}}\right)K_{\mathrm{c}}}{\ln\left(\frac{r_{\mathrm{e}}}{r_{\mathrm{w}}}\right)K_{\mathrm{c}}+K\ln\left(\frac{r_{\mathrm{w}}}{r_{\mathrm{w}}-x_{\mathrm{c}}(t)}\right)} \quad (14)$$

Substitute equation 14 into equation 10 and integrate it as:

$$\frac{\partial x_{\mathrm{c}}}{\partial t}=\frac{\frac{1}{2}\frac{q_{\mathrm{in}}(0)\ln\left(\frac{r_{\mathrm{e}}}{r_{\mathrm{w}}}\right)K_{\mathrm{c}}C_{\mathrm{solid}}}{\left(\ln\left(\frac{r_{\mathrm{e}}}{r_{\mathrm{w}}}\right)K_{\mathrm{c}}+K\ln\left(\frac{r_{w}}{r_{w}-x_{c}(t)}\right)\right)\pi r_{\mathrm{c}}\Delta L}-k_{\tau}\tau}{(1-\phi_{\mathrm{c}})\rho_{\mathrm{c}}} \quad (15)$$

Integrateequation 15 as:

$$x_{\mathrm{c}}(t+\Delta t)-x_{\mathrm{c}}(t)=\frac{\left(\frac{1}{2}\frac{q_{\mathrm{in}}(0)\ln\left(\frac{r_{\mathrm{e}}}{r_{\mathrm{w}}}\right)K_{\mathrm{c}}C_{\mathrm{solid}}}{\left(\ln\left(\frac{r_{\mathrm{e}}}{r_{\mathrm{w}}}\right)K_{\mathrm{c}}+K\ln\left(\frac{r_{\mathrm{w}}}{r_{\mathrm{w}}-x_{\mathrm{c}}(t)}\right)\right)\pi r_{\mathrm{c}}\Delta L}-K_{\tau}\tau\right)}{(1-\phi_{\mathrm{c}})\rho_{\mathrm{c}}}\Delta t \quad (16)$$

Equation 16 can be calculated for the cake thickness of next time step, and then we can calculate the intrusion flow of next time step, so equation 14 can be rewritten as :

$$q_{\mathrm{in}}\left(t+\Delta t\right)=\frac{q_{\mathrm{in}}(0)\ln\left(\frac{r_{\mathrm{e}}}{r_{\mathrm{w}}}\right)K_{\mathrm{c}}}{\ln\left(\frac{r_{\mathrm{e}}}{r_{\mathrm{w}}}\right)K_{\mathrm{c}}+K\ln\left(\frac{r_{\mathrm{w}}}{r_{\mathrm{w}}-x_{\mathrm{c}}(t+\Delta t)}\right)} \quad (17)$$

Combine equation 16 and 17, and we can obtain cake thickness and intrusivefluid flowat any time, which provides the basis for solutions to concentration distribution of invaded zone.

III. PREDICTION MODEL OF INVADING FLUID CONCENTRATION DISTRIBUTION

The concentration of invading fluid along the wellbore radial direction is variable, we assume that the formation porosity is constant, and the fluid is incompressible. Civan and Engler give the equation[6]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rD\frac{\partial C}{\partial r}\right)-\frac{u_{\mathrm{in}}(t)}{\phi(1-S_{\mathrm{or}})}\frac{\partial C}{\partial r}=\frac{\partial C}{\partial t} \quad (18)$$

$$u_{\mathrm{in}}(t)=\frac{q_{\mathrm{in}}(t)}{2\pi r_{i}\Delta L} \quad (19)$$

The initial conditions:

$$C(r_{\mathrm{w}},0)=C_{\mathrm{f}}\ C(r,0)=0$$

The boundary conditions:

$$C(r_{\mathrm{w}},t)=C_{\mathrm{f}}\ C(r_{\mathrm{e}},t)=0$$

$q_{\mathrm{in}}(t)$ can be solved by equation14. D is the diffusion coefficient，which is composed of convective diffusion coefficient D_{e} and molecular diffusion coefficient D_{m}，Donaldson and Chernoglazovgive the expression[7]:

$$D = D_{\mathrm{e}} + D_{\mathrm{m}} \quad (20)$$

The molecular diffusion can be ignored, because the convective diffusion coefficient is the main factor of fluid invasion process, and researchers have given the relationship between diffusion coefficient and the rate of fluid intrusion:

$$D = f u_{\mathrm{in}}^{g} \quad (21)$$

where：C —the concentration of invading fluid in the formation，$\mathrm{cm^3/cm^3}$；C_{f} —the concentration of invading fluidalong the borehole wall，$\mathrm{cm^3/cm^3}$；ϕ —formation porosity，dimensionless；S_{or} —residual oil saturation，dimensionless；$u_{\mathrm{in}}(t)$ — the velocity of drilling fluid invasion，$\mathrm{cm/s}$；r —the wellbore radius，cm；D —diffusion coefficient，$\mathrm{cm^2/s}$；f and g —experience or test coefficient。

Equation 18 can be rewritten as:

$$\frac{\partial C}{\partial t} = \frac{1}{r}\left(\left(r\frac{\partial D}{\partial r} + D\right)\frac{\partial C}{\partial r} + rD\frac{\partial^2 C}{\partial r^2}\right) - \frac{u_{\mathrm{in}}(t)}{\phi(1-S_{\mathrm{or}})}\frac{\partial C}{\partial r} \quad (22)$$

Substitute equation 19 and 21 into 22 and finish it as:

$$\frac{\partial C}{\partial t} = \alpha\frac{\partial C}{\partial r} + \delta\frac{\partial^2 C}{\partial r^2} \quad (23)$$

$$\alpha = \frac{1}{r}\left(f(1-g)\left(\frac{q_{\mathrm{in}}(t)}{2\pi r\Delta L}\right)^{g}\right) - \frac{\left(\frac{q_{\mathrm{in}}(t)}{2\pi r\Delta L}\right)}{\phi(1-S_{\mathrm{or}})} \quad \delta = f\left(\frac{q_{\mathrm{in}}(t)}{2\pi r\Delta L}\right)^{g}$$

Integrate equation23 as implicit equation:

$$A_i^{'}C_{i-1}^{t+1} + B_i^{'}C_i^{t+1} + C_i^{'}C_{i+1}^{t+1} = -C_i^{t} \quad (24)$$

$$A_i^{'} = \delta_i^{t+1}\frac{\Delta t}{\Delta r^2} - \alpha_i^{t+1}\frac{\Delta t}{2\Delta r}$$

$$B_i^{'} = -2\delta_i^{t+1}\frac{\Delta t}{\Delta r^2} - 1$$

$$A_i^{'} = \delta_i^{t+1}\frac{\Delta t}{\Delta r^2} + \alpha_i^{t+1}\frac{\Delta t}{2\Delta r}$$

Combined with boundary and initial conditions, equation 24 can be expressed as:

$$\begin{bmatrix} B_1^{'} & C_1^{'} & 0 & 0 & \cdots & 0 \\ A_2^{'} & B_2^{'} & C_2^{'} & 0 & \cdots & 0 \\ 0 & A_3^{'} & B_3^{'} & C_3^{'} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & & \vdots \\ 0 & \cdots & A_{\mathrm{N}-1}^{'} & B_{\mathrm{N}-1}^{'} & C_{\mathrm{N}-1}^{'} & \\ 0 & \cdots & & A_{\mathrm{N}}^{'} & B_{\mathrm{N}}^{'} & \end{bmatrix}\begin{bmatrix} C_1^{t+1} \\ C_3^{t+1} \\ C_3^{t+1} \\ \vdots \\ C_{\mathrm{N}-1}^{t+1} \\ C_{\mathrm{N}}^{t+1} \end{bmatrix} = -\begin{bmatrix} C_1^{t} + A_1^{'}C_{\mathrm{f}} \\ C_3^{t} \\ C_3^{t} \\ \vdots \\ C_{\mathrm{N}-1}^{t} \\ 0 \end{bmatrix} \quad (25)$$

Where: Δr —radial step of invaded zone，cm；Δt —time step，s.

The concentration of invading fluid at different timeand locations along the wellbore radial directioncan be given by solving equations 25. Therefore, the depth of contamination can be determined, thus providing basis for determining the permeability distribution ofpolluted zone.

IV. CONCLUSION

(1)The drilling damage mainly comes from solid particles invasion and filtrate invasion, and filtrate invasion is the major factor of formation damage in the process of drilling.

(2)The prediction model of drilling pollution parameters is established, including the prediction model of drilling fluid invasion and the prediction model of invading fluid concentration distribution, which can be used to predict the amount of drilling fluid invasion and pollution concentration distribution, thus providing the basis for reducing drilling damage and improving the production capacity.

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