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Research Article

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Horizontal well temporary chemical diverting acidizing simulation

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ABSTRACT

Long horizontal well usually encounters with different layers with varies reservoir characteristics and the damage degree is different in the horizontal section. Also, the distribution of damage zone is no homogeneous and it's difficult to deliver acid uniformly. The problem of acid delivery in the long horizontal well can be effectively solved by the use of temporary chemical diverting acidizing technology. Based on the chemical diverting acidizing mechanism and considering acid flowing in the formation and wellbore as an interactional unite, chemical diverting numerical model was developed and solved through coinciding reservoir and wellbore and the process of horizontal well temporary chemical diverting acidizing technology was modeled. The result shows that it can provide theoretical guidance for horizontal well chemical diverting technology.

Key words: chemical diverting agent, diverting numerical simulation, horizontal well, temporary plugging

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INTRODUCTION

Acidizing is one of the most important horizontal well stimulation method. The distribution of damage zone around the horizontal well is no homogeneous, which is caused by the different soaking time of drilling fluid and completion fluid in different horizontal section and the variation of reservoir characteristics (permeability anisotropy) encountered by horizontal well, and the damage degree of heel is serious than fingertip. In the process of horizontal well acidizing treatment, ensuring acid fluid flowing into the serious damage zone effectively is the key point of successful horizontal well acidizing treatment [1-3]. Chemical particle has many advantages, such as temporary diverting property, cheap, easy to use, etc. It can be used in acidizing treatment of horizontal well in which the distribution of permeability is heterogeneous. The experts over the world have done a lot of research about chemical particle system, supporting technology for field application and chemical diverting modeling of vertical well [4-6]. The study of horizontal well chemical diverting technology modeling is still paucity. Therefore, considering the acid lowing in the formation and horizontal wellbore as an interactional unity, horizontal well chemical diverting numerical model is developed and studied [7-8].

Temporary diverting model

Physical Model

There are axial flows (main flow) along the horizontal wellbore and radial flow towards the formation after acid fluid entering into the horizontal well section. Therefore, both the pressure along the wellbore and the sectional flow are changeable [9]. In order to establish the flowing model of the horizontal well section, we assume that: ① The box bounded reservoir is anisotropic; ② The length of horizontal well is L and the radius of section area is R_w; ③ The acid flowing pattern is laminar or turbulence; ④ There is no fluid flowing into the end of the horizontal well upstream and the acid heat-transfer process in the wellbore and formation is neglected; ⑤ Acid fluid is bumped into the formation at a constant rate, q_w; ⑥ The formation fluid flowing pattern is single steady seepage and satisfies with the Darcy law; ⑦ It is 1D axial flow for the fluid in the horizontal well.

Pressure Drop Model of Horizontal Wellbore
Assuming that the horizontal well length is L, the section radius is r_w, taking differential, d_x, away from the heel x. analyzing the fluid flowing process in the differential, shown in Fig.1.

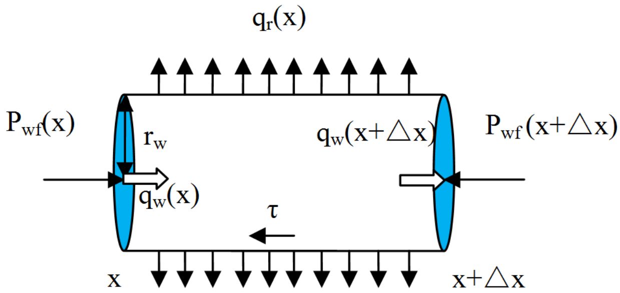

Fig.1: Unit division in the horizontal well

According to the continuity equation, we can get:

$$\frac{d}{dx}q_w(x) = -q_r(x) \tag{1}$$

External force impacting on the dominate differential is equal to the variation of fluid momentum in the dominate differential, that is:

$$Ap_{wf}(x) - Ap_{wf}(x+dx) - 2\pi r\tau dx = \rho Avdv \tag{2}$$

Differential equation of pressure drop in the horizontal wellbore can be obtained by solving the simultaneous equations of Eq. (1) and Eq. (2):

$$-\frac{dp_{wf}(x)}{dx} = \frac{\pi r_w}{A} f\rho \left[\frac{q_w(x) + \frac{q_r(x)}{2}dx}{A}\right]^2 + \rho\left[q_w^{\ 2}(x+dx) - q_w^{\ 2}(x)\right] \tag{3}$$

Expanding the equation above, neglecting the effect of second-order term and simplifying it:

$$-\frac{dp_{wf}(x)}{dx} = \frac{1}{\pi^2 r_w^{\ 5}} f\rho\left[q_w^2(x) + q_w(x)q_r(x)dx\right] - 2\rho q_w(x)q_r(x)dx \tag{4}$$

Chemical Diverting Acidizing Model
With the addition of chemical diverting agent and the acidizing process going on, the seepage channel will be expanded after the mineral being dissolved by acid and the low permeability filter cake will formed with the tiny particles accumulating on the borehole wall [10]. Flowing resistance will increase for the pressure drop caused by filter cake and which will divert the acid fluid to the section with less diverting agent. Therefore, we should pay attention to the redistribution of acid flow caused by two influencing factors above during the modeling process. Considering the effect of diverting agent and introducing the skin factor, S_{cake}, the flow rate of the i-th horizontal differential is:

$$q_{r,i} = \frac{2\pi k L_i\left(p_{wf} - p_e\right)}{\mu\left[\ln\frac{\sqrt{2}hI_{ani}}{r_w(I_{ani}+1)} + \pi\left(\frac{r_e}{hI_{ani}} - \frac{1}{2}\right) + s_i + s_{cake,i}\right]} \tag{5}$$

In which,

$$S_i = \left(\frac{k}{k_{d\,i}} - 1\right) ln\left[\frac{1}{I_{ani}+1}\left(\frac{r_{dH\,i}}{r_w} + \sqrt{\left(\frac{r_{dH\,i}}{r_w}\right)^2 + I_{ani}^{\ 2} - 1}\right)\right]$$

$$s_{cake} = \frac{\alpha k C_{da} \rho V}{2\pi l r_w^2 g}$$

Characteristic parameter α, concentration and density of chemical diverting agent, C_{da} and ρ, all of these parameters can be obtained through experiment.

Therein, k/k_d is formation damage degree; I_{an} is anisotropic index; r_{dH} is the elliptic damage area radius in the horizontal direction.

Interface movement model

Assuming that it is piston like displacement in the horizontal well, horizontal well chemical diverting acid process could be simplified as the process shown in Fig.2. With chemical diverting agent entering into the wellbore and displacing the wellbore fluid into formation continuously, the plug with diverting agent will penetrate into the formation gradually and form chemical filter cake [11]. In the pumping process, the interface I will move from heel to toe-end.

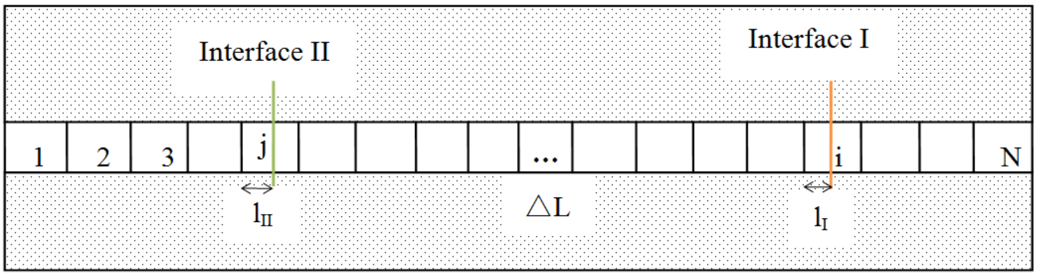

Fig.2: Interface movement in the horizontal well

After the next acid plug entering into formation, interface I and interface II may move together and the velocity equation of interface movement is:

$$\frac{dx_I}{dt} = \frac{\sum_{i=x_I}^{N} q_{wi}}{A}, \quad \frac{dx_{II}}{dt} = \frac{\sum_{i=x_{II}}^{N} q_{wi}}{A} \tag{6}$$

At the time $t+\Delta t$, positions of interface I and interface II are:

$$x_I\big|_{t+\Delta t} = x_I\big|_t + \frac{\sum_{i=x_I}^{N} q_{wi}}{A}\Bigg|_{x=x_I} \Delta t$$

$$x_{II}\big|_{t+\Delta t} = x_{II}\big|_t + \frac{\sum_{i=x_{II}}^{N} q_{wi}}{A}\Bigg|_{x=x_{II}} \Delta t \tag{7}$$

At the time n, interface I and II may be not at the mesh grid boundary divided. Therefore, skin factor of the mesh grid where the interface is should be processed. For example, interface I is in the i-th grid and interface II is in the j-th grid, then:

$$S_i^{n+1} = \frac{S_i^{n+1} l_I + S_i^n \left(\Delta L - l_I\right)}{\Delta L}$$

$$S_j^{n+1} = \frac{S_j^n l_{II} + S_j^{n+1} \left(\Delta L - l_{II}\right)}{\Delta L} \tag{8}$$

Coupling numerical model of acid flowing in the horizontal well and reservoir

Processing the coupling model by the use of implicit difference method (applying central difference on Eq. (1) and backward difference on Eq. (2)), we can get the implicit difference numerical model:

$$q_{w,i+1/2} - q_{w,i-1/2} = -\Delta x_i q_{ri} \tag{9}$$

$$p_{wf,i+1} - p_{wf,i} = -\frac{(\Delta x_{i+1} + \Delta x_i)}{2} \frac{f_i \rho q_{w,i+1/2}^2}{\pi^2 r_w^5} - \frac{1}{\pi^2 r_w^5} f \rho q_{w,i+1/2} q_{ri} + 2\rho q_{w,i+1/2} q_{ri} \tag{10}$$

Solution steps of the model

Solution method of the model is:

(1) Assuming that the fluid pressure in *N-th* wellbore unit is $P_{wf,\,N}$, and the imbibitions' volume of this unit is $q_{r,\,N}$;

(2) Calculating the pressure and imbibitions' volume, $P_{wf,\,N-1}$ and $q_{r,\,N-1}$, in the last wellbore unit by the use of Eq.(10). Calculating the total imbibitions' volume from this unit to the wellbore toe-end, $\sum q_r$, and the wellbore accumulated volume, $\sum V$. Determining the position of interface I;

(3) Similarly, the position of interface II can be obtained;

(4) Analogizing until the first wellbore unit. If the fluid flow-in, $q_{w,\,1/2}$, is equal to the injection volume, Q_{inj}, then we go to the next step; Otherwise, renovating $P_{wf,\,N}$ until $q_{w,\,1/2}$ is equal to Q_{inj};

(5) Repeating step (1) to step (4) until interface I coinciding with interface II, this means that diverting agent deposits on the borehole wall and diverting fluid enters into formation completely.

Case study

According to the numerical model and solution process of horizontal well chemical diverting acidizing treatment, we modeled the horizontal well chemical diverting acidizing process and the input parameter is: Reservoir pressure, p_e, is 18MPa; Drainage radius, r_e, is 1000m; Reservoir thickness, h, is 30m; Anisotropic index, I_{ani}, is 2; Horizontal permeability is 200mD; Horizontal wellbore length, L, is 200m; Horizontal wellbore radius, r_w, is 0.0896m (3-1/2''); The viscosity of injection fluid, μ, is 1mPa.s; Injection fluid density, ρ, is 1000kg/m^3; Injection rate, q, is 1.5m^3/min; Formation porosity, Φ, is 0.15; Formation damage degree, k/k_d, is 5. We studied the effect of acid displacement technology (chemical diverting acidizing, long interval acidizing), consumption and concentration of chemical particles on flow distribution along the horizontal wellbore.

Determination of Chemical Particle Characteristic Parameter α

By the use of Doerler equation, we applied fitting and regression analysis on diverting experiment data and got mean value of characteristic parameter, α, is 1.4×10^{12}m/kg and the matching results is shown in Fig.3. From the matching result, the relationship between reciprocal of flow, q, and accumulated injection volume, V, is nonlinear. Reason account for this phenomenon is that chemical particles formed filter cake in the core and the filter cake distribution is anisotropic. Therefore, we analyzed the linear portion to get characteristic index, α.

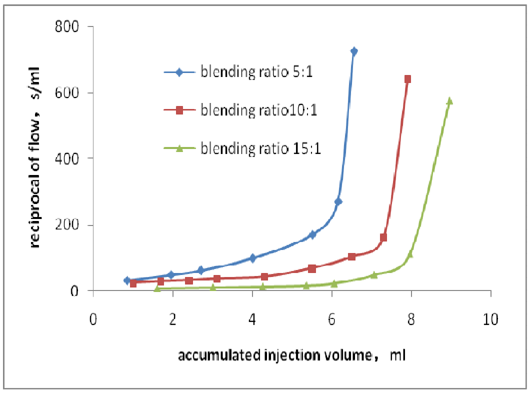

Fig.3: The regression result of chemical diverting experiment data

The Effect of Acid Distribution Technology on Acid Distribution along the Wellbore

Acid distribution technology has a significant influence on flow distribution along the wellbore (Fig.4). Flow distribution of long interval acidizing increases along the wellbore and the fluid flows into the toe-end is much larger than the fluid flows into the heel. There is a little acid flowing into the serious damaged heel and the pollution here could not be removed completely. Therefore, the acidizing effect will not be good. Treated by chemical diverting acidizing technology (total chemical particles volume is 8m^3, particle concentration, C_{da}, is 0.3), flow distribution along the wellbore tends to be plain, the fluid flow of heel increases dramatically and the fluid flow of toe-end decreases obviously [7]. The acidizing effect becomes better. As lots of filter cake formed by chemical particles accumulated at the wellbore toe-end, which would increase the skin factor of filter cake at the toe-end and improve the flow distribution of the whole wellbore.

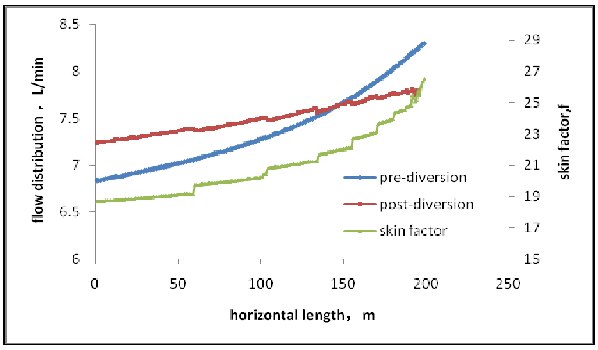

Fig.4: Modeling result of chemical diverting treatment process

The Effect of Chemical Particle Consumption Volume on Acid Distribution along the Wellbore

Chemical particle consumption volume is one of the most important factors influencing the horizontal well diverting effect (Fig.5). The more chemical particles we used, the more uniform flow distribution along the wellbore is. If the total chemical particle consumption is too small, the adjustment of flow distribution along the horizontal wellbore will be limited and the diverting effect will be worse. Therefore, acid flow distribution in the wellbore could be improved by increasing the total chemical particle consumption volume [5]. But, too large chemical particle volume would lead to dramatic increasing of pumping pressure and it asks for higher requirements on surface equipment and the safety risk of treatment is higher too. Therefore, in order to improve the effect of temporary chemical diverting acidizing, we should optimize the chemical particle consumption volume by considering the effect of reservoir anisotropy, well length, completion method, etc.

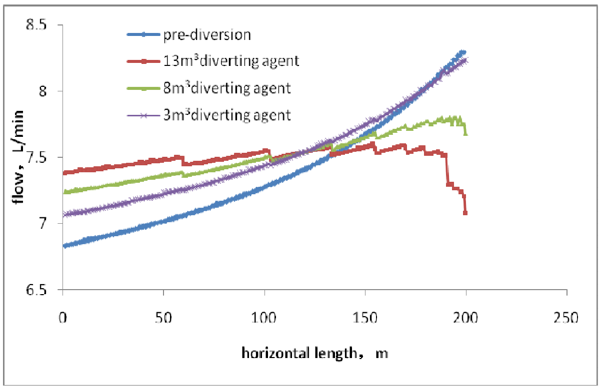

Fig.5: The effect of diverting agent on flow distribution in the wellbore

The Effect of Chemical Particle Concentration on Acid Distribution along the Wellbore

Chemical particle concentration has a significant effect on acid flow distribution along the wellbore. The larger chemical particle concentration is, the more diverting agent entering into the toe-end is, the less chemical particle entering into the heel is, and the more uniform acid distribution is. The less chemical particle concentration is, the smaller filter cake on-way resistance is. Although there is more diverting agent entering into the heel, no uniform acid distribution phenomenon along the wellbore still couldn't be improved obviously. Therefore, no uniform flow distribution along the wellbore could be effectively improved by increasing chemical particle concentration (shows in Fig.6) and the effect of diverting acidizing could be improved too.

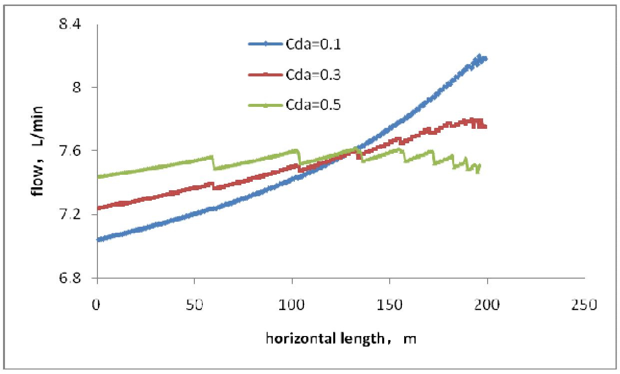

Fig.6: The effect of diverting agent concentration on flow distribution in the wellbore

CONCLUSION

Considering variable quality pipe flow in the horizontal wellbore and radius percolation to the formation of diverting agent (chemical particle) as a unit, we developed the chemical diverting numerical model by coinciding formation with wellbore and studied the effect of diverting agent on improving flow distribution along the wellbore and the influencing factors of flow distribution along the wellbore.

No uniform flow distribution along the wellbore could be significantly improved by the use of chemical diverting acidizing technology.

Flow distribution along the wellbore mainly influenced by acid distribution technology, chemical particle consumption volume and particle concentration.

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