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Optimization of Separant Displacement in Artificial Barrier Height-Control Hydraulic Fracture

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ABSTRACT: *The main mechanism of artificial barrier height control is to change the stress difference between pay layer and barrier layers, but the artificial barriers method is mainly studied by experiment, and rarely in theoretical till now. Based on the hypothesis of (that) artificial barrier can be treated as a porous filter cake, this paper studied the laws of separant floating or sinking, and the porosity, permeability and specific resistance of the composition medium of separant. With the 3D fracture extent model, it can be developed into the theoretical model of artificial barrier laying optimization, programmed the model. At last use the oilfield data to verify the program.*

Key Words： *Artificial Barrier; Fracture Height Control; Hydraulic Fracture; Separant Optimization*

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I. INTRODUCTION

Controlling the fracture height within the production zone is a key factor in the success of hydraulic fracturing. When the oil layer is very thin or when the barrier layer is a weak stress layer, the fracture may penetrate the production layer into the barrier layer. When the fracture height is too large, due to the limited fracturing scale, the fracture length will be correspondingly reduced, which will not achieve the purpose of deep penetration fracturing and increase production. The post-pressing output will also decrease rapidly due to the small control area of the crack, which greatly reduces the effect of fracturing. More seriously, if the reservoir is adjacent to the water layer, the excessive extension of the fracture height may press through the water layer, making the oil and gas well see water or flooded too early. Therefore, the control of fracture height is critical for fracturing of thin layers, weak stress shielding layers and bottomed water reservoirs.

The use of separant to form an artificial barrier can effectively prevent the extension of the fracture height. During the fracturing construction process, a small-diameter low-density floating separant or a high-density sinking separant is added to form a dense barrier layer at the end of the fracture extending vertically, which increases the vertical extension resistance, thereby controlling the fracture within the layer. However, if the separant enters the formation, it will block the pores of the formation and affect the seepage of the formation. If the addition time and dosage of the separant are not well controlled during the fracturing process, the effect of the high elongation of the barrier seam may not be obtained, and even the formation or crack may be blocked, which greatly reduces the fracturing effect. Therefore, the study of the dose of the separant and its addition time is very important.

1. Establishment of fracture geometry calculation model

In order to quantitatively optimize the placement of the artificial compartment, the fracture geometry calculation model is first established. Based on Palmer's pseudo-three-dimensional hydraulic fracture width calculation model, the continuity equation and pressure distribution equation were improved, and the mechanical calculation equation of fracture morphology was added to obtain the fracture geometry model.

1）Fracture width equation[1]

$$W(f_L)=\frac{8(1-u^2)l}{\pi E}\int_{f_L}^{1}\frac{f_2 df_2}{\sqrt{f_2^{\,2}-f_L^{\,2}}}\int_0^{f_L}\frac{P(f_1)df_1}{\sqrt{f_2^{\,2}-f_1^{\,2}}} \quad (1)$$

Where, $f_L = y/l$, $l = h/2$ is the fracture half height, f_1, f_2 are integral variables less than f_L and greater than f_L respectively.，$P(f_1)$ is the net internal pressure at the point y at the fracture height direction.

Let $f_{L'} = (H/2)/l = H/h$,H is the thickness of the layer, h is the height of the fracture. The solution to the above equation is discussed below for the case where |y| is greater than H/2 or less than H/2.

Net pressure distribution:

$$P(y)=\begin{cases}P_f-S_1 & |y|<H/2\\ P_f-S_2 & |y|>H/2\end{cases}$$

Where, P_f is the pressure inside the fracture, S_1 and S_2 are the minimum principal stresses of the production layer and the cover layer, respectively.

2）Continuity equation[2]

$$\frac{\partial q_{xx}}{\partial x}+\frac{\partial q_{xy}}{\partial y}=-q_{xl}-\frac{\partial W_x}{\partial t}+q_{xI} \qquad (2)$$

Where: $q_{xx}(q_{xy})$ — volume flow in the direction (y direction) on the main line x in the y direction (x direction) unit length;

$|q_x|$ — the total flow at the main line x;

$$|q_x|=(q_{xx}^2+q_{xy}^2)^{\frac{1}{2}}$$

q_{xl} — within the unit body △x, the volume loss rate per unit area of the fracture wall surface;

$$q_{xl}(x,y,t)=\frac{2C(x,y)}{\sqrt{t-\tau(x,y)}} \qquad (3)$$

Where: $C(x,y)$ — comprehensive filter loss coefficient;

$\tau(x,y)$ — the moment when the point (x, y) on the fracture wall begins to filter out;

q_{xI} — at x, the injection rate of the fracturing fluid per length of the fracture cross-sectional area; except for the area adjacent to the perforation section of the well, q_{xI} is zero;

W_x — the width of the fracture at x.

3）Flow equation[3]

According to the equation of viscous fluid motion (Naver- Stocker equation) and the introduction of the power flow equation, the pressure distribution equation of the fracturing fluid in the fracture length and the fracture height can be obtained.

$$\frac{\partial p_{xx}}{\partial x}+\eta'[\frac{|q_x|}{W_x^{\,2}}]^{n'-1}\frac{q_{xx}}{W_x^{\,3}}=0 \qquad (4)$$

$$\frac{\partial p_{xy}}{\partial y}+\eta'[\frac{|q_x|}{W_x^{\,2}}]^{n'-1}\frac{q_{xy}}{W_x^{\,3}}=\rho F_{xy} \qquad (5)$$

Where:

η' — the viscosity is related to the commonly used power law fluid coefficients K. The relationship of n' is:

$$\eta'=K[(2+\frac{1}{n'})\cdot 2^{\frac{n'+1}{n'}}]^{n'}$$

ρF_{xy} — the unit volume force generated by the gravity of the fracturing fluid at x;

$|q_x|$, q_{xy} , p_{xy} , W_x —— flow at point x, vertical flow, vertical differential pressure, fracture width.

4）Mechanical calculation model of fracture height[4]

When the fracture height reaches the occlusion layer, the leading edge will be passivated instead of being semi-elliptical. The passivation stress intensity factor of $K_p=\xi K_{ic}$, K_{ic} is the rock fracture toughness, ξ = 3 ~ 4.

Combined with the Geertsma formula, it can be further deduced that when the crack does not reach the upper and lower occlusion layers:

$$L = \frac{Q_i}{32\pi H_0 C^2}(\pi W_o + 8S_p)\left[e^{\alpha^2} erfc(\alpha) + \frac{2\alpha}{\sqrt{\pi}} - 1\right] \quad (6)$$

$$\alpha = 8C\sqrt{\pi t} /(\pi W_o + S_p)$$

When the upper barrier is laminated and the lower barrier is not pressed:

$$L = \frac{P_1}{P_2}\frac{\xi_1 r_1 \sqrt{Q_i}}{4\pi C}\left\{(\pi W_o + 8S_p)\left[e^{\alpha^2} erfc(\alpha) + \frac{2\alpha}{\sqrt{\pi}} - 1\right]\right\}^{1/2}$$

$$\Delta_1 = L/\left(\xi_1 r_1 P_1 / P_2\right)^2 - H_0 \qquad (7)$$

式中：P_1,P_2—— the stress difference at the end of the fracture in the reservoir and the compartment, MPa;
W_o—— fracture width, m;
S_p—— priming loss, m^3;
r_1—— the ratio of the barrier to the fracture toughness of the reservoir;
Δ_1—— the depth of the fracture pressed into the compartment, m.
The lower barrier laminate is similar to the upper barrier.
When the upper and lower compartments are pressed, you can get:

$$A \approx 2\pi LB = \pi L(H_0 + \Delta_1 + \Delta_2)$$

$$= \frac{Q_i}{8\pi C^2}(\pi W_o + 8S_p)\left[e^{\alpha^2} erfc(\alpha) + \frac{2\alpha}{\sqrt{\pi}} - 1\right]$$

According to the influence of in-situ stress, Δ_1 and Δ_2 satisfy the following relationship:

$$H_d = H_p /[1-(1-\frac{H_o}{H_u})(\frac{\sigma_u - \sigma}{\sigma_d - \sigma})^2]$$

$$\Delta_1 = H_u - H_o\text{；}\ \Delta_2 = H_d - H_o$$

The depth and the length of the fracture that presses through the upper and lower compartments are immediately available.

5）Model establishment

According to the above four equations and their boundary conditions, a closed equations about the pressure, fracture width, fracture height and length of the fracture can be obtained, and the basic model of fracture geometry calculation is formed.

2. Artificial compartment laying mechanism and optimization

After the pre-liquid is injected to form a fracture of a certain scale, the fracturing fluid carrying the sinking separant (silt sand, etc.) and the floating separant (hollow microbead) is injected, and the hollow microbeads are quickly placed under buoyancy. At the top of the new fracture, the silt sinks to the bottom of the fracture under the action of gravity, thereby forming a low-permeability or impervious artificial compartment at the top and bottom interfaces of the fracture, so that there is a stress difference before and after the partition. Inter-grounding changes the pressure distribution within the fracture, thereby controlling the vertical extension of the fracture.

According to the basic principle of controlling the fracture height by the artificial compartment, the artificial partition is equivalent to the "filter cake" formed by the porous medium of particle accumulation.

1）Study on the law of sinking and floating of separant

When the separant sinks, its sink/floating speed takes a positive number. If the separant is a floating separant, the particle sink/floating speed $u_{s(d)}$ takes a negative number. For the convenience period, only the case where $u_{s(d)}$ takes a positive value is discussed below, that is, only the calculation of the sedimentation velocity of the particles is studied.

The sedimentation law of the separant in the joint is affected by the particle concentration, the fracture wall surface and the particle sphericity. The sedimentation velocity of the separant particles in the fracture can be obtained as follows:

$$u_{rs(d)} = v_{s(d)} \times f_w \times f_c \times f_e \qquad (8)$$

Where, $v_{s(d)}$—— the free settling velocity, the expression in the power rate fluid is:

$$u_{s(d)} = \frac{d_p^2(\rho_s - \rho)g}{18K'}\left[\left(\frac{u_{s(d)}}{d_p}\right)^2 + \dot{D}_2^2\right]^{\frac{1-n'}{2}} \quad (9)$$

式中：K'—— consistency coefficient, Pa·s；

$\dot{D}_2$ —— the shear rate produced by the flow, s^{-1}；

d_p —— separant particle size, mm；

$\rho_s - \rho$ —— difference in solid-liquid density, kg/m^3；

Equation (9) is solved by an iterative method, where $\dot{D}$ is related to the flow velocity distribution of the liquid in the slit.

f_c —— particle concentration interference settlement coefficient;

$$f_c = \frac{u_{rs(d)}}{u_{s(d)}} = \frac{C_f^2}{10^{1.82(1-C_f)}}$$

Where: C_f —— the volume fraction (decimal) of the liquid in the mixture.

f_W —— the influence coefficient of the fracture wall;

When the Reynolds number $N_{Re}<1$,

$$f_W = \frac{u_{rs(d)}}{u_{s(d)}} = 1 - 0.6526\left(\frac{d_p}{W}\right) + 0.147\left(\frac{d_p}{W}\right)^3 - 0.131\left(\frac{d_p}{W}\right)^4 - 0.0644\left(\frac{d_p}{W}\right)^5$$

Where: d_p ——particle size, cm;

W —— fracture width, cm.

When $N_{Re}>100$, $f_W = \frac{u_{rs(d)}}{u_{s(d)}} = 1 - \left[\frac{d_p}{2W}\right]^{\frac{3}{2}}$

If $1 \le N_{Re} \le 100$, then take the value by linear interpolation.

f_e—— Spherical influence coefficient;

$$f_e = \frac{C_d N_{Re}}{24}$$

2）"Filter cake" physical property study

① Porosity and compressibility

The "filter cake" porosity formed by the deposition of the spacer according to the porosity definition is:

$$\phi = \frac{V_v}{V_b} = 1 - \frac{\rho_b}{\rho_s}$$

Where: ρ_b —— the apparent density of the particle stack;

ρ_s —— the true density of the particles.

The compression factor $\alpha \approx \phi\alpha_p$, α_p is the void compression factor.

② Permeability

According to the Kozeny—Carman equation, the permeability of the "filter cake" is:

$$k = c_0 \frac{\phi^3}{(1-\phi)^2 {M_s}^2} = c_0 \frac{\left(\phi_0 - \frac{\sigma_{sd}+\sigma_{sp}}{\rho_s}\right)^3}{\left(1-\phi_0 - \frac{\sigma_{sd}+\sigma_{sp}}{\rho_s}\right)^2 {M_s}^2}$$

Where: σ_{sd} —— the amount of seepage particles deposited on the surface of the pores per unit volume of rock, g/cm^3;

σ_{sp} —— the amount of seepage particles that can block the pore throat in a unit volume of rock, g/cm^3;

M_s—— specific surface area of the particles;

$$M_s = \frac{k_s}{\rho_s d_s}$$

k_s—— the shape factor of the particles, kg/m^3; the values are shown in the table below.

Particle shape	Spherical and cubic	Columnar	Octahedron	Positive cone	tetrahedron	Flaky	Extremely thin
k_s	6.0	7.8	8.5	9.7	10.0	16.7~17.5	55.6~160.0

c_0—— constant, Carman recommends taking 1/5.

③ Particle sorting effect

It is generally believed that when the particle size is less than 15% of the throat diameter, the particles can smoothly pass through the porous medium without causing damage; when the particle size is 15% to 30% of the throat diameter, the particles enter the pore medium and deposit on the pore surface, reducing the porosity and causing damage; when the particle size is greater than 30% of the throat diameter, the particles are easily "bridged" at the throat, thereby restricting the subsequent particles from continuing to enter, causing the particles to accumulate at the "bridge"; when the particle size is close to 30% to 50% of the throat diameter, it is most likely to block the pores; when the particle size is larger than 73% of the throat diameter, the particles cannot enter the pore medium and cause clogging directly on the surface of the pore medium.

If the pore diameter is equivalent to the diameter of the inscribed circle of the triangle formed by the tangent line connecting three tangent separators, the porous medium formed by the particle accumulation can be obtained according to the most closely arranged particle arrangement. The pore diameter is $d_p = \frac{\sqrt{3}}{6} d \approx 0.289d$, where d is the diameter of the equal-sized particles.

Assuming that the sorting degree of the separant is ω, the nominal diameter is d, and the particle diameter distribution that does not conform to the standard obeys the uniform distribution (that is, the probability of falling in the interval of the unit length section is the same), it is known from the above theory that the artificial volume formed by the separant per unit volume In the compartment, $\frac{1}{2} \times \frac{\sqrt{3}}{6}(1-\omega) \approx 0.144(1-\omega)$ volume of particles can affect the permeability of the artificial compartment by means of particle seepage. Among them, 30%, that is, 0.043 (1-ω) volume of particles will produce pore surface deposition when percolating, ie $\sigma_{sp} = 0.043(1-\omega)$, while the volume of 0.101 (1-ω) particles percolates will block the pore throat, ie $\sigma_{sp} = 0.101(1-\omega)$.

④ "filter cake" specific resistance

The specific resistance of the filter cake is an important parameter in the percolation, and the value of the value directly reflects the ease of percolation.

According to Darcy's law:

$$Q = k\frac{A\Delta P}{\mu h} = \frac{A\Delta P}{\mu a_m w_c} = \frac{A\Delta P}{\mu a_m h \rho_s (1-\phi)}$$

Where: Wc—— dry "filter cake" mass per unit area, kg/m2;

a_m—— average mass resistance, m/kg;

$$a_m = \frac{1}{k\rho_s(1-\phi)}$$

3）Artificial compartment layout optimization

① Isolator dose optimization

Assume that at time t, at the x point in the crack, the crack presses through the upper layer, at this time according to the formula:

$$L_x = \frac{P_{x1}}{P_{x2}} \frac{\xi_1 r_{x1}\sqrt{q_{xx}\Delta x}}{4\pi C}\left\{(\pi W_o + 8S_p)\left[e^{\alpha^2} erfc(\alpha) + \frac{2\alpha}{\sqrt{\pi}} - 1\right]\right\}^{1/2} \quad \Delta_{x1} = L_x / \left(\xi_1 r_{x1} P_{x1} / P_{x2}\right)^2 - H_x$$

To lay the artificial compartment to control the crack within the pay zone, you need to make △1=0, then

$$\Delta_{x1} = L_x / \left[\xi_1 r_{x1}(P_{x1} + \Delta P_{xab}) / P_{x2}\right]^2 - H_x = 0$$

Where: ΔP_{xab}—— he pressure difference of the fracturing fluid through the artificial compartment, MPa.

The quality of the separant required to lay the artificial barrier that produces the ΔP_{xab} pressure drop loss is:

$$m_x = A_{xy} w_c = A_{xy} \frac{(q_{xy}\Delta x)\mu a_m}{A_{xy}\Delta P_{xab}} = \frac{(q_{xy}\Delta x)\mu a_m}{\Delta P_{xab}}$$

②Optimization of laying time of release agent

Supposing that the crack at x just breaks the compartment at the time of t, and the particle o reaches the surface of artificial compartment, according to the principle of sedimentation/ uplifting of particles in crack, time that the particles need to settle or float to the artificial compartment from point x of the main streamline is as follows:

$$\Delta t_{s(d)} = \frac{h_x}{u_{rs(d)}}$$

That is, at the moment of t-$\triangle t_{s(d)}$, particle o is at point x of the main streamline, and the horizontal velocity u_{xx} of the main streamline at point x at the moment of t-$\triangle t_{s(d)}$ is

$$u_{xx} = \frac{q_{xx}}{W_x}$$

q_{xx}——fracturing flow per unit vertical length, which can be obtained by flow distribution equation.

The time required for particle o to pass through each section of △x in the fracture length direction can be obtained by:

$$\Delta t_i = \frac{\Delta x}{u_{(x-i\Delta x)x}^{(t' - \sum_0^{i-1} \Delta t_j)}}$$

where：$t' = t - \Delta t_{s(d)}$

Δt_i——time required for particle o to migrate from (x-i△x) to [x-(i-1)△x], s;

$u_{x'x}^{t''}$——at the moment of t', the horizontal velocity of particle o at x',m/s。

According to the boundary condition $u_{x=0} = Q_0/(L_0H_0)$, the time taken by particle o from the crack opening to the main streamline x can be obtained by:

$$\Delta t_{xx} = \sum_0^n \Delta t_i$$

Where: n＝x/△x，integer.

Then, according to wellbore flow, the time for particle o to migrate from wellhead to fracture can be calculated as Δt_{wh}. Thus, the total time for particle o to migrate from wellhead to artificial compartment can be obtained:

$\Delta t = \Delta t_{wh} + \Delta t_{xx} + \triangle t_{s(d)}$

Therefore, in order to lay artificial compartment at x in the fracture at time t, we need to add compartment from the wellhead at t-△t, but generally the artificial compartment is laid before the crack break the compartment to control the crack height within the production layer effectively. As a result, the release agent should be added 1~2 minutes earlier than t-△t.

3. Programming
Program flow chart is shown in Fig.1.

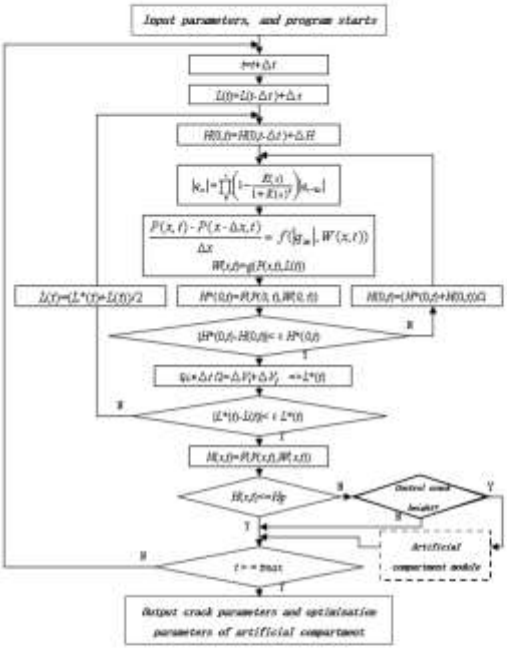

Fig.1 Program flow chart

The flow chart of artificial compartment module is shown in Fig.2.

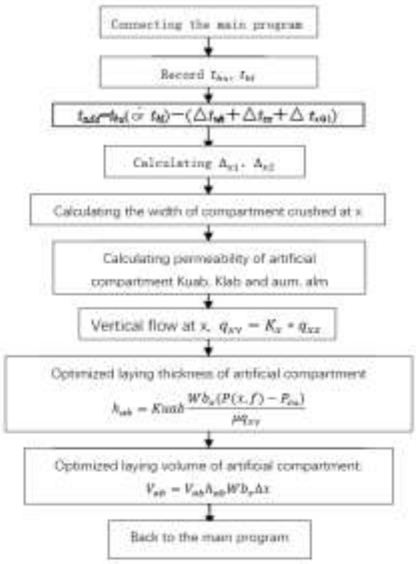

Fig.2 The flow chart of artificial compartment module

4. Example verification
In order to compare the effect of controlling crack height using artificial compartment, we first calculated the results of non-artificial compartment fracturing.

①Fracturing example without artificial compartment
Data of a fractured well are as follows:

Perforating section, m	2551-2559	Reservoir thickness, m	8
Fracturing fluid density, kg/m3	1040	Reservoir pressure, MPa	28
Effective permeability, 10-3μm2	2.3	Porosity, %	12

The fracture simulation results is shown in Fig.3. the calculated results are basically consistent with the field data.

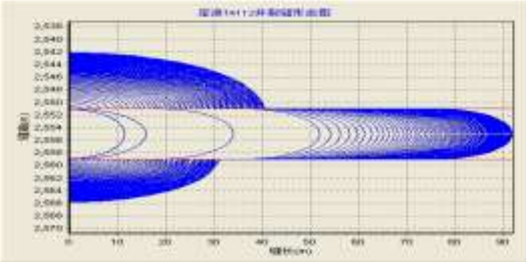

Fig.3 Crack morphology without artificial compartment

It can be seen that after the crack reaches the interface of oil compartment, there is a extension rolling process of more than 20 meters before breakthrough compartment. This is the crack end passivation in the expansion model of crack height in mechanics, which is controlled by the passivation coefficient ξ. It can also be seen that the cap layer has been crushed within a short period of time (about 9 minutes), causing large crack height. The oil layer is seriously exceeded, which reduces the efficiency of fracturing and stimulation effect.

②Adding artificial compartment

The release agent data is shown in the following table.

	Floating agent	Sinking agent
Apparent density, kg/m^3	650	2200
True density, kg/m^3	800	2800
Particle diameter, m	0.0002	0.00008
Coefficient of compressibility, 1/MPa	2×10^{-7}	2×10^{-7}
Sorting rate, decimal	0.95	0.98
Sphericity of particle, decimal	0.97	0.97

The calculation results are shown in Fig.4.

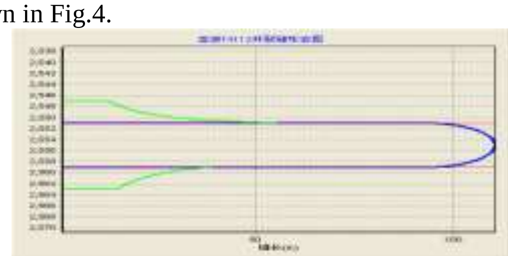

Fig.4 Crack morphology after adding artificial compartment

The green line in the figure indicates the thickness of the release agent. It can be seen that by adding $0.53m^3$ of floating release agent from 7 minutes after the fracturing at a gradually increasing dose and by adding $0.33m^3$ of sinking release agent from 7.5 minutes after the fracturing at a gradually increasing dose, the crack is better controlled within the production layer, the maximum dynamic crack length increases from 92m to 110m, the maximum crack width increases from 1.78cm to 1.85cm, and the fracturing fluid efficiency also increases from 27.9% to 34.4%.

II. CONCLUSIONS

Through the above research, the following conclusions can be drawn:

(1) By adding artificial compartment, the crack height can be better controlled and the fracturing effect can be improved;

(2) The artificial compartment can be modeled by a "filter cake" formed by a porous medium composed of a release agent.

(3) When the crack extends vertically to the wall of the partition, it is not directly opened in an elliptical shape, but has a passivation process.

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