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Influence of In-situ Stress Distribution on Selection of Fracturing Fluid Backflow Technology

C. Zhou*[§], X. Wu, H. Li, Z. Ren and Y. Xin

Department of Petroleum Engineering, China University of Petroleum (Beijing), Beijing, China

The distribution of in-situ stress has significant influence on fracture propagation direction so as to affect the selection of the fluid backflow technology. The influences on the longitudinal cracks in fracture propagation direction, caused by vertical stress distribution of the interlayer-oil layer, was firstly analyzed. Then, the settling rule of proppant within the fractures during the flowing back process was analyzed. Meanwhile, the bottomhole pressure curves under different nozzle diameters after shut-in were obtained by the volume balance principle. Therefore, the facture closure time and the maximum proppant settling distance were determined. Finally, combined with the field data, fracturing fluid backflow process, which considered the influence of in-situ stress, was optimized. Calculation shows that the location of oil layer in the in-situ stress zone and the proppant settling distance have close relations with the selection of fracturing fluid backflow technology. Hence, the optimization of fracturing fluid backflow technology requires consideration of the key factors above.

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1. Introduction

In the flowback stage after fracturing operation, field engineers always intend to get fractures with high conductivity and obtain good distribution of proppant in the oil layers by controlling the flowback rate. In fact, the design of fracturing fluid backflow should concern not only the influence of critical velocity, but also the influences of the settling rule of proppant in the flowback process and the relative location between oil layer and fracture. However, the latter two factors are often neglected. In this paper, firstly we discuss the vertical stress distribution of the interlayer-oil layer, and then we analyze the longitudinal propagation trend of fractures and the settling rule of proppant during the flowback process. Finally we propose the methods used to optimize the fracturing fluid flowback technology.

2. The influence of vertical stress

When the pressure of fracturing fluid in wellbore can generate new fracture, this pressure is called formation fracture pressure, which can be expressed as [1]:

$$P_{\mathrm{f}} = 3\sigma_h - \sigma_H - \alpha P_{\mathrm{p}} + S_{\mathrm{t}}, \qquad (1)$$

where, P_{f} is formation fracture pressure, MPa; σ_h is minimum in-situ stress, MPa; σ_H is maximum in-situ stress, MPa; α is effective stress factor, dimensionless; P_{p} is formation pore pressure, MPa; S_{t} is formation tensile strength, MPa.

In the fracturing operation process, fractures always generate in the lowest in-situ stress section of the minimum principal stress plane of the formation, due to the asymmetrical distribution of vertical in-situ stress. When the fluid pressure in the fracture exceeds the minimum horizontal principal stress of this section, the fracture will penetrate this section to propagate. On the other hand, when the fluid pressure in the fracture is lower, than the minimum horizontal principal stress of this section, the fracture will be blocked by this section and cease developing.

Because of the various vertical distributions of minimum horizontal principal stress in the oil layers and interlayers, different forms of fractures are generated, which can be classified into ten situations, as described below [2, 3].

2.1. *Oil layer is located in low in-situ stress zone*

When the oil layer is located in low in-situ stress zone while the interlayers are located in high in-situ stress zone, the fracture will be restricted in the low in-situ stress zone by the interlayers. According to the different locations of oil layer in the low in-situ stress zone, four situations can be obtained as follows.

1. Oil layer is located in the lower section of the low in-situ stress zone, and fracture propagates toward the upper interlayer, as is shown in Fig. 1a;
2. Oil layer is located in the middle section of the low in-situ stress zone, and fracture propagates toward both the upper and lower interlayers, as is shown in Fig. 1b;
3. Oil layer is located in the upper section of the low in-situ stress zone, and fracture propagates toward the lower interlayer, as is shown in Fig. 1c;
4. Oil layer overlaps with the low in-situ stress zone, and fracture is restricted within the range of the low in-situ stress zone, as is shown in Fig. 1d.

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*corresponding author; e-mail: `zc_cup@sina.cn`

[§] Chao Zhou is a doctoral candidate majoring in Oil-Gas Field Development Engineering in China University of Petroleum (Beijing). He holds a master's degree in Petroleum Engineering from China University of Petroleum (Beijing). He has participated in several oil and gas field development projects and is familiar with this direction.

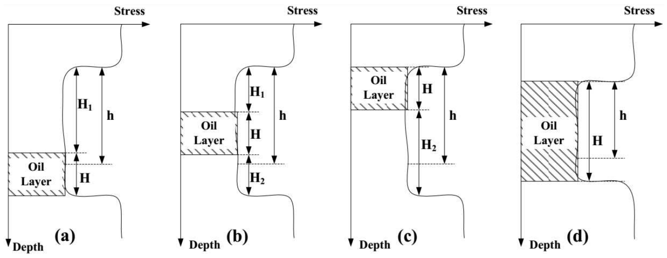

Fig. 1. Fracture propagation when the oil layer is in low in-situ stress zone.

Notes: H – thickness of fractured oil layer, m; H_1 — fracture height above the oil layer, m; H_2 — fracture height beneath the oil layer, m; h — maximum proppant settling distance in the fracture, m. The fracture height $H_f = H_1 + H + H_2$.

2.2. *Oil layer is located in medium-high in-situ stress zone*

When the oil layer is located in medium-high in-situ stress zone, the fracture will penetrate the low in-situ stress zone, and two situations can be obtained as follows.

1. The fracture propagates toward the lower interlayer, as is shown in Fig. 2a;
2. The fracture propagates toward the upper interlayer, as is shown in Fig. 2b.

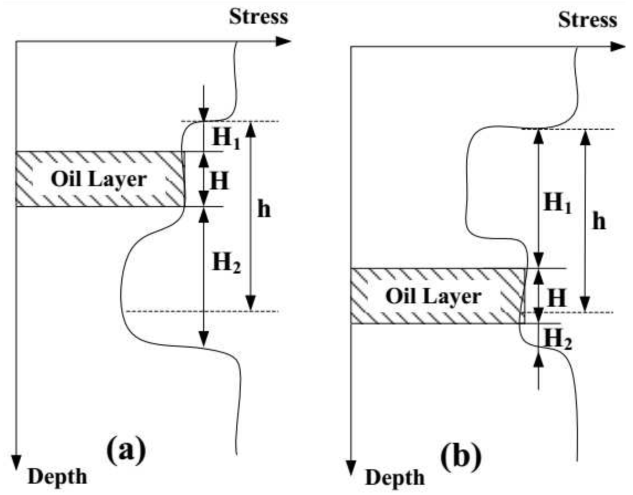

Fig. 2. Fracture propagation when the oil layer is in medium-high in-situ stress zone.

2.3. *Oil layer is located in high in-situ stress zone*

When the oil layer is located in high in-situ stress zone, the oil layer is difficult to be fractured. Even if fracture is generated, the fracture will penetrate all low in-situ stress zones, and it will be hard to control the fracture height, as is shown in Fig. 3.

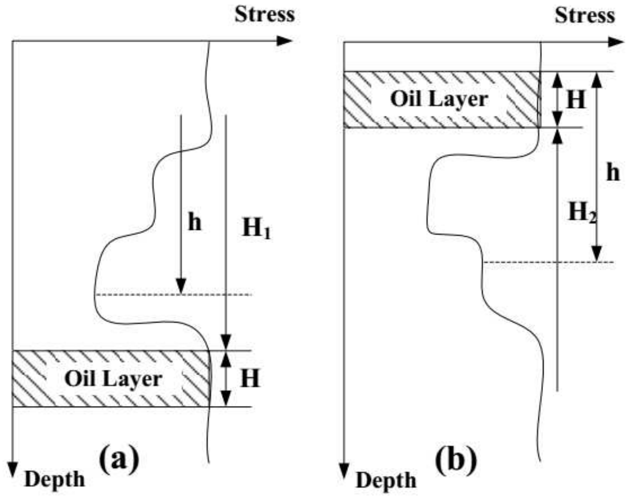

Fig. 3. Fracture propagation when the oil layer is in high in-situ stress zone.

2.4. *Oil layer is located in the interface of high stress zone and low stress zone*

When there is a large gap of stress between the high and low in-situ stress zones, the fracture will be restricted within the low in-situ stress zone, as is shown in Fig. 4.

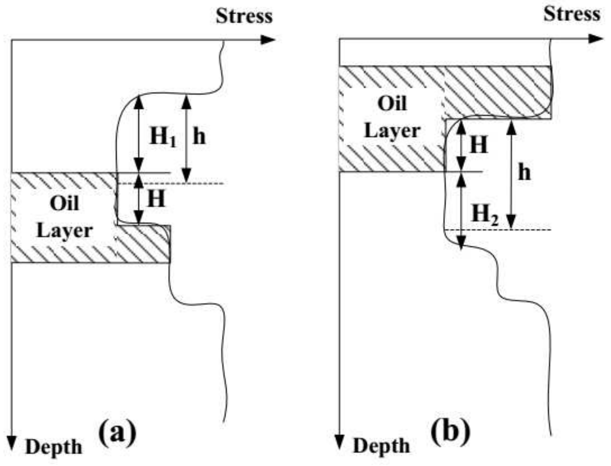

Fig. 4. Fracture propagation when the oil layer is in the interface of high and low stress zone.

3. Analysis of proppant settling

The prevailing backflow technologies mainly include low rate backflow technology [4] and forced closure technology [5]. Low rate backflow technology delays fracture closure by controlling the flow rate, reducing proppant crushing and flowback. Forced closure technology promotes fracture closure before proppant settling by aggressive backflow, and packs proppants in the fracture.

The proppant settling distances in different backflow technologies lead to different proppant distribution profiles. Assuming that the actual proppant backflow rate is less than the critical rate. As a result, proppant flowback will not occur. In this case, only the influence of proppant settling distance on propped fracture is considered. When $h < H_1$, the maximum proppant settling distance is less than the fracture height above the oil layer, fracturing effect is best. When $H_1 < h < (H_1 + H)$, the maximum proppant settling distance is larger than the fracture height above the oil layer, the upper part of the fracture is not propped, fracturing is less effective. When $(H_1 + H) < h$, the entire fracture is not propped, fracturing operation fails [6].

3.1. Calculation of fracture closure time

According to the volume balance principle, when fracturing fluid backflow starts, the change of the fracture volume equals the sum of the fracturing fluid total leak-off volume and the fracturing fluid flowback volume [7], which can be expressed as:

$$\Delta V_\mathrm{f} = V_\mathrm{f}(t_0) - V_\mathrm{f}(t) = V_\mathrm{ls} + V_\mathrm{out}, \tag{2}$$

where, ΔV_f is the fracture volume change after shut-in, m^3; V_out is the fracturing fluid flowback volume, m^3. Both of them are functions of the bottomhole pressure. V_ls is the fracturing fluid total leak-off volume after shut-in, m^3, which can be calculated by t, time after shut-in [8, 9]. The bottomhole pressure can be calculated by iteration method using Eq. 2. As a result, we can obtain the relationship between bottomhole pressure and time, as well, as the relationship between wellhead pressure and time. Pressure vs. time curves under different nozzle diameters also can be plotted by iteration using Eq. 2. By using the fracture closure pressure and the bottomhole pressure curve, fracture closure time can be determined.

3.2. Calculation of proppant terminal settling velocity

The singular granule free settling velocity [10] can be expressed as:

$$u_\mathrm{t} = \sqrt{\frac{4\left(\rho_\mathrm{s} - \rho_\mathrm{l}\right) g d_\mathrm{p}}{3\rho_\mathrm{l} C_\mathrm{D}}}. \tag{3}$$

When calculating the proppant terminal settling velocity, we consider the correction of inter-granular interference:

$$u_\mathrm{ts} = u_\mathrm{t}\left(1 - C_\mathrm{s}\right)^n. \tag{4}$$

And the correction of wall interference:

$$u_\mathrm{tw} = f_\mathrm{w} u_\mathrm{ts}, \tag{5}$$

where, u_t is singular granule free settling velocity, m/s; ρ_l is fluid density, $\mathrm{kg/m^3}$; ρ_s is proppant density, $\mathrm{kg/m^3}$; g is gravitational acceleration, $\mathrm{m/s^2}$; d_p is proppant diameter, m; C_D is the drag coefficient, dimensionless; u_ts is settling velocity with inter-granular interference considered, m/s; C_s is proppant volumetric concentration, dimensionless; n is empirical constant, dimensionless; u_tw is proppant terminal settling velocity, m/s; f_w is wall effect correction coefficient, dimensionless.

The fracture closure time and proppant terminal settling velocity can be determined using Eq. 2 to Eq. 5. Finally, the maximum proppant settling distance can be calculated.

3.3. Case study

The case of a fractured well X is demonstrated. The formation data, fracturing data and wellbore data are listed in Table I. The in-situ stress profile is shown in Fig. 1b.

TABLE I

Formation data, fracturing data and wellbore data.

Type	Parameter	Value	Unit
formation data	formation rock elastic modulus	17360	MPa
	Possion's ratio	0.16	dimensionless
	fracture clousre pressure (surface)	8	MPa
fracturing data	volumetric flow rate	0.0567	$\mathrm{m^3/s}$
	total leak-off coefficient	2.5×10^{-4}	$\mathrm{m/min^{0.5}}$
	fracturing fluid viscosity	1.8×10^{-3}	Pa s
	fracture height	40	m
	shut-in time	64.7	min
	wellhead instantaneous shut-in pressure	11.8	MPa
	fractured formation thickness	19	m
	fracturing fluid density	1120	$\mathrm{kg/m^3}$
	fluid behavior index	0.5647	dimensionless
	average proppant diameter	0.8	mm
	proppant particle density	2750	$\mathrm{kg/m^3}$
	average proppant concentration	0.4	dimensionless
wellbore data	well depth	1366	m
	wellbore diameter	0.124	m

According to Eq. 2, wellhead pressure vs. time curves under different nozzle diameters can be plotted, as is shown in Fig. 5. The x-axis is time after shut-in and the y-axis is the wellhead pressure. The fracture closure time under different nozzle diameters can be determined by using the fracture closure pressure.

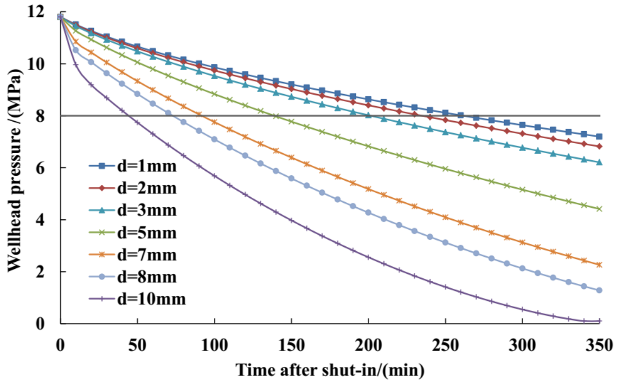

Fig. 5. Wellhead pressure vs. time curves under different nozzle diameters.

The maximum proppant settling distances under different nozzle diameters before fracture closure can be calculated using terminal settling velocity and fracture closure time, as is shown in Fig. 6. From the data of the case, when $H_1 = 10$ m and $H_2 = 11$ m, the maximum proppant settling distance should be less than 10 m and the optimum nozzle diameter is between 6 mm and 7 mm.

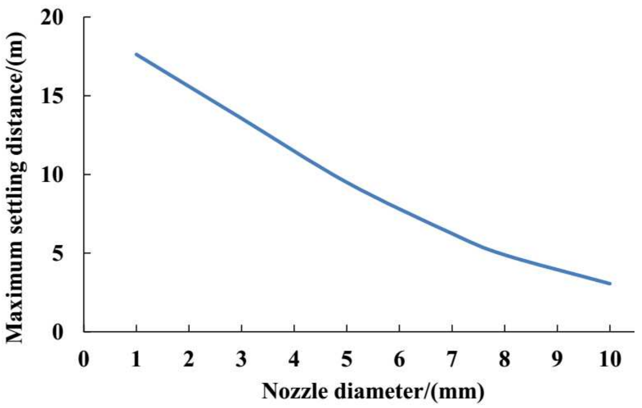

Fig. 6. Maximum proppant settling distances for different nozzle diameters.

4. Selection of backflow technology

From the analysis above, the selection of backflow technologies for formations in different in-situ stress zones can be achieved by calculations according to different in-situ stress profiles [11], as is shown in Table II. In the fractured well X, for instance, the oil layer is located in the middle section of the low in-situ stress zone, and the maximum proppant settling distance should be less than 10 m. As a result, immediate backflow is required, and flow rate should be higher than leak-off rate, the optimum nozzle diameter is about 6 ∼ 7 mm.

TABLE II

Oil layer locations and corresponding selection of backflow technologies.

Formation position within stress profile	Selection of backflow technologies
bottom of low stress zone	low backflow rate, settling permitted, reduced propped fracture height
middle of low stress zone	immediate backflow, flow rate higher than leak-off rate
top of low stress zone	forced backflow, avoiding settling of proppant
entire section of low stress zone	immediate backflow, flow rate higher than leak-off rate
bottom of medium-high stress zone	low backflow rate,limiting settling permitted, reduced propped fracture height
top of medium-high stress zone	forced backflow, avoiding settling of proppant
bottom of high stress zone	very low backflow rate, forced backflow is not recommended
top of high stress zone	forced backflow, avoiding settling of proppant
interface of high stress zone and low stress zone (a)	low backflow rate, settling permitted, reduced propped fracture height
interface of high stress zone and low stress zone (b)	forced backflow, avoiding settling of proppant

5. Conclusions

The distribution of in-situ stress has significant influence on fracture propagation direction and affects the selection of the backflow technologies. The design of backflow technologies should consider the relative positions of formation and fracture. When in-situ stress barriers ensure fracture to propagate within the formation, immediate backflow is required, and flow rate should be higher than fluid leak-off rate in the fracture. This backflow technology allows proppant to migrate towards perforations. When fracture propagates upwards, low backflow rate is required and proppant migration due to settling and leak-off is allowed, which would increase proppant concentration in fracture and reduce propped fracture height. When fracture propagates downwards, proppant settling will occur during fracture propagation and fracture closure process, and forced backflow should be adopted. In this case, even under high backflow rate condition, proppant may still be packed only near the perforations and not the entire fracture length, fracturing operation is less effective.

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