Fracturing Fluid Leak-off for Deep Volcanic Rock in Zhungeer Basin: Mechanism and Control Method

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Abstract. The deep volcanic reservoir in Zhungeer Basin is buried in over 4000m depth, which is characterized by complex lithology (breccia, andesite, basalt, etc.), high elastic modulus and massive natural fractures. During hydraulic fracturing, hydraulic fracture will propagate and natural fractures will be triggered by the increasing net pressure. However, the extension of fractures, especially natural fractures, would aggravate the leak-off effect of fracturing fluid, and consequently decrease the fracturing success rate. 4 out of 12 fracturing wells in the field have failed to add enough proppants due to fluid loss. In order to increase the success rate and efficiency of hydraulic fracturing for deep volcanic reservoir, based on theoretical and experimental method, the mechanism of fracturing fluid leak-off is deeply studied. We propose a dualistic proppant scheme and employ the fluid loss reducer to control the fluid leak-off in macro-fractures and micro-fractures respectively. The proposed technique remarkably improved the success rate in deep volcanic rock fracturing. It bears important theoretical value and practical significance to improve the hydraulic fracturing design for deep volcanic reservoir.

Keywords. Volcanic rock, fracturing fluid, leak-off, natural fracture, hydraulic fracturing

1 Introduction

According to the acoustic imaging logging data and core observation, the deep volcanic reservoir in Zhungeer basin, Xinjiang Province, is naturally developed with macro-frature, micro-fracture and induced fracture, which is triggered by temperature field variation during the drilling fluid encountered hot formation in the drilling process.

The most difference between hydraulic fracturing in naturally fractured volcanic reservoir and conventional homogeneous reservoir is the fracturing fluid leak-off mechanism [1-2]. In the hydraulic fracturing process for conventional homogeneous sandstone reservoir, the fracturing fluid leak-off is mainly controlled by matrix permeability, fracturing fluid viscosity and reservoir fluid compressibility, but for the naturally fractured volcanic, the leak-off is primarily dominated by natural fractures. The leak-off rate is dynamic, and related to net pressure in fracturing process [3], so it is hardly preestimated in hydraulic fracturing design. Due to natural fractures and the stress variation from far to near field, the fracture propagation path will curl, swerve, bifurcate and intertwined with each other, finally turn into a fracture network system. [4-6]. By the influence of high elastic modulus in the deep reservoir and the interaction of multiple propagating fractures, the fracture width is limited, leads to prematurely screen-out during fracturing operation. Thus in naturally fractured volcanic reservoir, fracturing fluid leak-off is hardly controlled because of the complexity of fracture propagation and natural fracture [7-8]. Pad fluid largely leaks off from extended major fracture into natural fractures, which cause proppant block up at the end of crack, and pressure rocket up, resulting in the failure of fracturing treatment. Thus for deep volcanic reservoir, controlling natural fracture leak-off in hydraulic fracturing design is crucial to improve the success rate of treatment.

2 Natural fracture width with leak-off effect

In the process of volcanic rock fracturing, the extended hydraulic fracture intersects with natural fracture, as shown in Figure 1, when the fluid pressure within the hydraulic fracture exceeds the normal stress imposed on the natural fracture surface, the natural fracture will be activated, and tensile failure occurs, then the fracturing fluid leak-off from hydraulic fracture into the natural fracture system will increase dramatically.

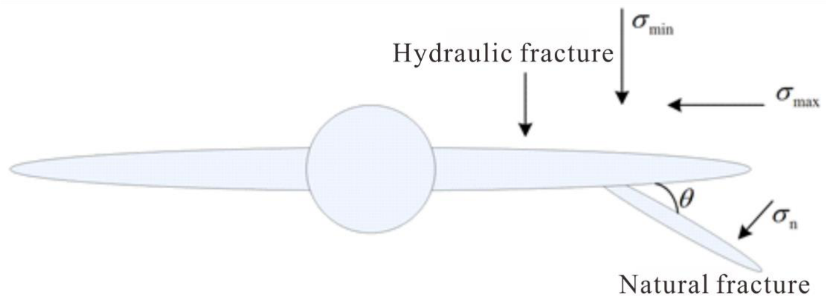

Fig. 1. Intersection graph between the hydraulic fracture and the natural fracture.

The dynamically width of natural fracture is a key factor to influence fracturing fluid loss, as well as a basic criterion to select fluid loss reducer. Based on the mutual relationship between the natural fracture direction and hydraulic fracture orientation controlled by in-situ stress, considering the hydraulic fracture will intersect with natural fracture in hydraulic fracturing process, given the fluid pressure in major fracture, the equation for natural fracture width can be written as [9]:

$$W(x) = \frac{2(1-\nu^2)h_f(p(x)-\sigma_n(x))}{E} \tag{1}$$

where $W(x)$ is the maximum width of fracture along extended direction, E is the rock Young's modulus, h_f is the fracture height, ν is the Poisson's ratio, $\sigma_n(x)$ is the normal stress of the fracture in the extended direction, $p(x)$ is the fluid pressure along fracture.

The fracture extension pressure can be expressed as the form of net pressure:

$$p(x) = p_{net}(x) + \sigma_{min} \tag{2}$$

where $p_{net}(x)$ is the net pressure in fracture, σ_{min} is the minimum horizontal principal stress.

The normal stress imposed on natural fractures surface is [10]:

$$\sigma_n = \frac{\sigma_{max}+\sigma_{min}}{2} + \frac{\sigma_{max}-\sigma_{min}}{2}\cos 2(90^\circ - \theta) \tag{3}$$

where σ_{max} is the maximum horizontal principal stress, θ is the angle between the natural fracture and the horizontal maximum stress.

3 The selection of the fluid loss reducer in open natural fracture

For the natural fracture opened by hydraulic fracturing, when proppant diameter is less than natural fracture width, it can move in the fracture unrestrictedly, could not effectively form a blockage, so that fracturing fluid leak-off is out of control. According to the criterion of the triple proppant diameter, fracture width should be greater than 2.5 d_{prop}, when using slug that respectively consist of 70/140, 40/70, 20/40 sand to control fracturing fluid loss, the minimum fracture width that can prevent proppant from moving is as shown in Table 1

Table 1. The minimum width of facture that proppant could get through.

Proppant mesh	Proppant diameter mm	The minimum fracture width under different sand concentration (mm)		
		5%	10%	>25%
70/140	0.106-0.212	0.29	0.36	0.636
40/70	0.212-0.425	0.58	0.73	1.275
20/40	0.425-0.85	1.15	1.45	2.55

The low sand concentration (sand concentration<10%) totally can not control the leak-off dominated by natural fractures when fracture width is over 0.36mm, therefore, when a single type proppant is used alone, the effect that decreasing fracturing fluid leak-off is very limited. The low concentration medium sand can form a bridge when fracture width is less than 1.45mm, but it cannot reduce the leak-off, due to its high permeability characteristics. It can be known that, in the width of 0.4-1.5mm fracture, the minor proppant such as 100 mesh cannot form effective blockage. Although the large propping agent such as 20/40 mesh could form effective blockage, the natural fracture permeability which packed by proppant is high, fracturing fluid leak-off is out of control.

In order to control the leak-off through open natural fractures, we proposed a dualistic proppant scheme. Specifically, using the mixed propping agent in hydraulic fracturing, the large proppant are used to provide high conductivity, and the small propping agent aims at controlling fluid leak-off, as is shown in Figure 2. First of all, the temporary blocking agent with continuous particle size distribution is added according to fracture geometry, which can effectively block off different sizes of fractures and the gap between temporary blocking agents. Only from the reasonable particle size distribution, can we minimize the leak-off process.

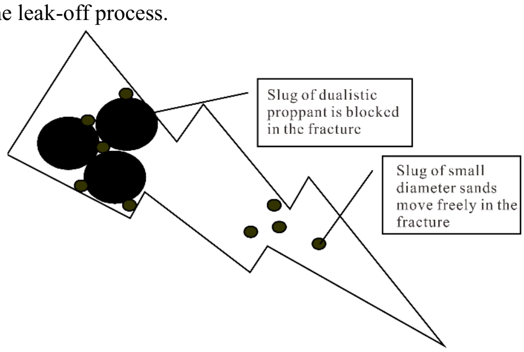

Fig. 2. Controlling fluid leak-off by dualistic proppant scheme.

When employ the dualistic proppant scheme to decrease the leak-off, the movement of small particles among large particles can influence fracture conductivity, and it also affects the stimulation effects, therefore, it is essential to optimize the diameter of small proppants.

Assuming the large particles are ideal spheres, which are closely packed in the fracture, as shown in figure 3. Four adjacent spheres form a cavity, and there is a smaller ball locates in this cavity, which can be considered to a throat formed by the ideal large ceramsite. The ball diameter is 0.41 times of the solid ball according to geometric relationship, for the 0.45-0.90mm (20/40 mesh) proppant in hydraulic fracturing, the distribution of diversion channel gap diameter is in the range of 0.18 to 0.36mm, According to the principle of bridging by 1/3 diameter, the channel allows small particles whose diameter are below 0.06mm to get through, the 0.06-0.36mm particles will block the gap, and large particles whose diameter over 0.36 mm will be excluded. So all particles whose diameter is under 0.06mm (240 mesh) may have the potential to affect the final conductivity of propped fracture. Therefore, when choosing large particles whose diameter are between 0.45 and 0.90mm（20/40 mesh）in hydraulic fracturing, small diameter particles can be selected in the range of 70 to 200 mesh.

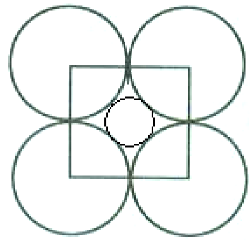

Fig. 3. The plane diagram of the gap volume among four accumulated particles.

When employ the dualistic proppant scheme to control the leak-off, the effect of sealing natural fractures can be achieved by adjusting the proportion of the two elements, through the indoor experiments, the sealing effect of two kinds of proppants for 20-40 mesh and 100 mesh ceramsite was compared. Assuming the sand concentration is 5kg/m^2, the experimental results are shown in Table 2.

Table 2. The permeability of mixed proppant for 20-40 mesh and 100 mesh.

Closure stress (MPa)	100% 100 mesh (D)	65%100 mesh 35%20-40 mesh (D)	35%100 mesh 65%20-40 mesh (D)	100% 20-40 mesh (D)
7	9.2	9.15	18.35	160.0
14	8.5	9.13	17.31	158.0
28	7.3	8.97	15.80	140.0
42	6.0	8.60	13.70	980.0
56	4.0	7.05	12.12	250.0

The experimental results show that fracture permeability varies with particle concentration ratio. Under the condition of the same closure stress, the smaller the proportion of small particles, the lower the permeability of the packed fracture, the better the control of leak-off.

4 The selection of fluid loss reducer for closed natural fractures

Conventional fluid loss reducer is often used to control leak-off in closed natural fractures, such as silica flour, clay, which result in the large proppant hardly enter natural fractures, the defect of this type material is that, once getting into the formation and pore channels, it will cause permanently damage to formation. To solve this problem, the JL-1 fluid loss reducer was selected, the JL-1 is a light yellow powder and can be dissolved in crude oil but water. The JL-1 prepared by the C9 component which generated in the process of pyrolysis petroleum, its fineness is over 95%, the softening point is above 70℃, and the dissolution is shown in table 3~4.

The results show that the JL-1 can be totally dissolved in kerosene but not dissolvable in water and acidizing fluid, and still maintain the characteristics of solid particles in water and acidizing fluid, ensured that no solid particles, which might block up the oil flow passage, be left over before production stage.

Table 3. The solubility of JL-1 fluid loss reducer.

Solvent	Acidizing fluid	Fresh water	Kerosene
Concentration of JL-1（%）	2	2	2
Dissolution	Insoluble	Insoluble	Completely soluble

Table 4 is experiment result that the JL-1 decreases the leak-off under the condition of 90℃, 2MPa. When increasing the JL-1 by 1%, the time of producing liquid will be put off by 15 minutes, and the leak-off coefficient of building capacity decreased by nearly 1/2; when increasing the JL-1 by 2%, the leak-off coefficient will decrease more. It can be seen that, there is a significant effect on reducing fracturing fluid leak-off, when the JL-1 is added to the fracturing fluid. In the actual construction, the general design of fluid loss reducer ratio is 2%, you can get a better effect of controlling leak-off to meet the requirements of fracturing operation in micro-fractured formation.

Table 4. The effect of reducing leak-off with JL-1.

Item	Total filter loss（ml）	C ($m/min^{1/2}$)	Experimental phenomenon
Control sample	12.5	8.5×10^{-4}	Filtrate oozes out soon after pressurized
1% JL-1	7.2	4.6×10^{-4}	Filtrate oozes out in 15min after pressurized pressure
2% JL-1	6.0	3.5×10^{-4}	Filtrate oozes out in 30min after pressurized

In order to analyze the JL-1 effect on core permeability, we analyzed the damage of the JL-1 to core permeability in water based gel fracturing fluid by using the artificial core, which is shown in Table 5.

Table 5 Core permeability with different JL-1 concentration

JL-1 concentration（%）	Core quantity（piece）	K_g ($10^{-3}\mu m^3$)	K_{oil} ($10^{-3}\mu m^3$)	Total filter loss（ml）	Damage rate（%）
0	3	9.7-25.6	16.18	3.62	16.8
2	4	10.1-25.2	16.64	2.36	15.2

Table 5 shows that the damage rate caused by gel fracturing fluid in 2% concentration is equivalent to no using fluid loss reducer. It implies that formation damage rate caused by fluid loss reducer is low.

5 The treatment design for multiple fractures leak-off

The design of multi-fractures leak-off control technology for target volcanic reservoir is based on the following principles:

- Using the packed particles which match fracture width for temporary blockage;
- Employing the dualistic proppant scheme to substantially improve the effect of reducing fracturing fluid leak-off ;
- Choosing the large size ratio of temporary plugging agent, the effect of reducing fracturing fluid leak-off will be better;
- The minimum particle size should meet the requirements of no relative movement in the space among large particles.

Considering the distribution of natural fractures width for target reservoir is in the range of 0.01~0.19mm, the net pressure is in the range of 5-6MPa, according to G function analysis. The angle between the natural fracture and the maximum principal stress is 23~35°, the average elastic modulus is 30152MPa, the maximum horizontal principal stress is 82MPa, and the minimum horizontal principal stress is 68MPa.

The calculation result of Equation (1)~(3) shows that: the natural fracture will occur tensile failure, and the open width of natural fractures is mainly 1 to 3mm, in the actual fracturing operation, the proppant system employing the dualistic proppant scheme, which consists of 20/40 mesh particles and less 100 mesh sand. According to the principle of fluid loss control technology for multi-fractured reservoir, the control of multi-fracture leak-off process should be carried out by using the following particle combination when using proppant slug to control multiple fractures leak-off in pad stage.

Table 6. Pad schedule for multi-fractures leak-off treatment.

Equivalent fracture width(mm)	Total sand concentration(%)	Medium sand concentration %	Small sand concentration %	Slug quantity	fluid loss reducer %
<0.5	3-6	0	3-6-9 (0.09-0.224mm)	3	1
0.5-1.0	4-10	2-4-6(0.45-0.9mm)	2-4(0.09-0.224mm)	3	1
1.0-3.0	5-10	3-6(0.45-0.9mm)	3-6-9(0.09-0.224mm)	3	1.5
>3.0	6-15	3-6-9(0.45-0.9mm)	3-6(0.224-0.45mm)	3	1.8

6 Conclusion

(1) Based on mechanism of natural fracture controlled fracturing fluid leak-off in the fracturing process of volcanic reservoir, a proposed method combining dualistic proppant scheme and fluid loss reducer could meet the requirements of reducing the leak-off in deep volcanic reservoir fracturing by decreasing the open fractures width and controlling the fluid loss in closed fractures;

(2) For the dualistic proppant scheme to control fluid leak-off in open fractures, the size and proportion of different particles are vital in design process, the selection of different proppant size has been demonstrated by theory, the experimental evaluation of different particle proportion effect on the leak-off is carried out, which provides theoretical basis for dualistic proppant scheme design;

(3) The experimental results for fluid loss reducer in closed fractures show that: the JL-1 has good oil solubility, the effect of reducing the leak-off is evident, and the damage rate to reservoir is low, which satisfies the requirements of reducing the fluid loss for deep volcanic reservoir;

(4) Based on the open behavior and extending behavior of natural fractures during fracturing operation in volcanic reservoir, the pad fluid schedule for multi-fractures leak-off treatment is optimally designed, which could remarkably improve the success rate in hydraulic fracturing for target reservoir.

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