Study on wellbore annular sealing technology based on the influence of fracturing operation in low permeability oilfield

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Abstract: At present, the fracturing technology has been very mature and is widely used in oil and gas field production operation. However, the fracturing operation will cause periodic changes in wellbore internal pressure and generate alternating stress. Due to the material factors of casing and cement sheath, the deformation of the two is inconsistent after stress, and then the damage of cement sheath and the failure of wellbore annulus seal occur. After water injection development, it is easy to produce channeling risk, so the performance of cement sheath is crucial. In view of this problem, through the theoretical analysis, experimental analysis and organic combination analysis of wellbore annulus cement ring sealing, the critical failure threshold of wellbore annulus cement ring under fracturing operation is given, which provides certain guidance for improving wellbore annulus sealing and reducing the risk of channeling after fracturing operation in the future.

Key words: Fracturing operation; cement ring for borehole; alternating stress; sealability

1. Introduction

Borehole annulus is composed of casing and cement sheath. In the whole life cycle of oil and gas wells, it must withstand the test of downhole high temperature and high pressure environment, fluid erosion and corrosion, and fracturing, acidification, water injection and other construction operations, and always maintain the sealing of borehole annulus. But with the deepening of oilfield development, tight oil, shale oil and other unconventional reservoirs gradually increased, fracturing technology has been widely used. Fracturing operation will cause periodic changes in wellbore internal pressure and generate alternating stress. Due to the material factors of casing and cement sheath, the deformation is inconsistent after stress, and then the damage of cement sheath and the failure of wellbore annulus seal occur. Therefore, the requirements for cement sheath are also improved accordingly.

At present, the analysis methods of wellbore annulus sealing mainly include theoretical analysis and experimental analysis [1-6]. In the theoretical analysis, due to the different assumptions and boundary conditions of the model, the results are different. In the experimental analysis, due to the different size effects and simulation conditions of the established model, the results have different degrees of one-sidedness. In the process of well construction, one of the methods is often used to analyze, and the understanding of wellbore annular sealing is insufficient. Therefore, it is necessary to carry out theoretical analysis, experimental analysis and organic combination analysis of wellbore annulus cement ring sealing, and give the critical failure threshold of wellbore annulus cement ring under fracturing operation, which provides a basis for improving wellbore annulus sealing and reducing the risk of channeling after fracturing operation.

2. Theoretical analysis of cement sheath sealing in borehole annulus

Under the action of alternating stress caused by fracturing operation, the elastic-plastic deformation of cement sheath in borehole annulus occurs. According to the maximum shear stress theory[7-8] :

$$\sigma_\theta - \sigma_r = \sigma_s \tag{1}$$

σθ、σr、σs-- the circumferential stress, radial stress and shear failure strength of the borehole annulus cement ring.
σs -- the critical strength threshold of the borehole annulus cement ring.

Assuming that the casing in the borehole is in an ideal state, the borehole regularity and the cement filling degree are all ideal, according to the thick-walled cylinder theory, the maximum value of the differential stress borne by the cement ring in the annulus of the borehole can be calculated, which is located at the contact surface of the cement ring in the casing, and the following results can be obtained:

$$\sigma_{s\max} = 2\left(p_i \text{-} p_o\right) r_o^2 / \left(r_o^2 \text{-} r_i^2\right) \tag{2}$$

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r_i 、 r_o -- the inner and outer radius of the wellbore cement sheath

p_i 、 p_o -- The pressure on the contact surface of wellbore cement sheath with casing and formation

According to Mohr-Coulomb 's law, pi and p0 is the function of elastic modulus and Poisson 's ratio of casing, cement stone and formation rock. Since only the elastic modulus of cement stone is variable in all parameters under a borehole condition, the formula (2) can be rewritten as

$$\sigma_{s\max} = f(E_e) \tag{3}$$

This formula (3)is the critical strength threshold of wellbore annulus cement sheath, assuming that δ is the influencing factor of wellbore annulus cement sheath channeling, and pe is the compressive strength of cement stone. From the above formula,

$$\delta = \sigma_{s\max} / P_e = f(E_e) / P_e \tag{4}$$

λe-- The sealing coefficient of cement sheath in borehole annulus

$$\lambda_e = e^{1-\delta} = e^{1-f(E_e)/P_e} \tag{5}$$

λea- Sealing coefficient of contact surface between cement sheath and casing

λer- Sealing coefficient of contact surface between cement sheath and stratum

$$\lambda_{ea} = e^{1-f_{ea}(E_e)/P_{ea}} \tag{6}$$

$$\lambda_{er} = e^{1-f_{er}(E_e)/P_{er}} \tag{7}$$

Pea-- Bond Strength of Interface between Cement Ring and Casing、

Per-- Bond strength between cement sheath and stratum interface

λ--- Comprehensive Sealing Coefficient of Cement Ring in Hole Ring

$$\lambda = \{\lambda_e, \lambda_{ea}, \lambda_{er}\}_{\min} \tag{8}$$

Under a certain downhole fracturing environment, the comprehensive sealing coefficient of cement sheath in wellbore annulus is related to the elastic modulus and compressive strength of cement stone, the bond strength between cement sheath and casing contact surface, and the bond strength between cement sheath and formation contact surface. When the sealing coefficient is less than 1, the wellbore annulus cement ring seal failure occurs. When the sealing coefficient is 1, the wellbore annulus cement ring is in a critical sealing failure state. When the sealing coefficient is greater than 1, the wellbore annulus cement ring does not have sealing failure, and the greater the a, the greater the probability of no sealing failure. In the field application, considering various factors such as casing centrality, borehole regularity and cement filling, the sealing coefficient can be divided into three levels: low risk when the sealing coefficient is 1.5. Taking 105 °C and alternating stress 70 MPa as an example, the sealing coefficient of cement sheath in borehole annulus under various elastic modulus and compressive strength is calculated respectively.

Table 1. Sealing coefficient of annular cement ring under 105 °C and 70 MPa alternating stress(ρ=1.90g/cm^3)

compressive strength MPa	Elastic modulus /GPa				
	5	6	7	8	9
70	2.02	1.93	1.81	1.72	1.66
65	1.99	1.81	1.74	1.67	1.58
60	1.85	1.74	1.66	1.58	1.53
55	1.77	1.67	1.60	1.54	1.51
50	1.68	1.61	1.59	1.51	1.43
45	1.64	1.57	1.52	1.29	1.18

The results show that the sealing coefficient of conventional cement with elastic modulus of 9 GPa decreases from 1.51 to 1.18 after 40 times of alternating stress, which is in a medium risk state. After 40 times of alternating stress, the sealing coefficient of toughened cement with elastic modulus 5GPa decreases from 1.77 to 1.64, which is still in a low risk state. Through this analysis method, the sealing property of annulus cement sheath in borehole can be evaluated, and its sealing coefficient threshold can be given.

3. Experimental analysis on sealing performance of cement sheath in borehole annulus

At present, when analyzing the sealing performance of cement sheath in borehole annulus through experiments, on the one hand, the macroscopic measurement methods in traditional standards, such as elastic modulus, compressive strength, gelling strength, etc., are used, and the measurement results cannot be well in line with the actual downhole fracturing environment. On the other hand, simulated borehole annulus measurement method is used, but there are still many one-sided aspects in the simulation of size, formation environment and stress process. Therefore, a new type of cement sheath sealing experimental device for borehole annulus was established. API casing was used to participate in the experiment, soft material was used to simulate the formation, and multiple sets of independent pressure systems were used to simulate the whole process of borehole annulus sealing. By setting different pressure parameters of the device, the purpose of simulating the actual downhole fracturing environment is achieved.

The experimental device is used as follows :

(1) The cement slurry is prepared in proportion and injected rapidly between the simulated casing and the formation;

(2) Closed end cover, pressure casing internal pressure, cement layer pressure and formation pressure are applied respectively, and the temperature is increased according to the set program

(3) After 7 days to simulate the downhole fracturing experiment. In the simulation experiment, under the influence of simulated fracturing, the cement ring continuously receives alternating stress, and the sealing performance of cement ring in wellbore annulus can be

analyzed by evaluating the fluid flow in the simulated formation.

Fig 1 Experimental device for cement sheath sealing in borehole annulus

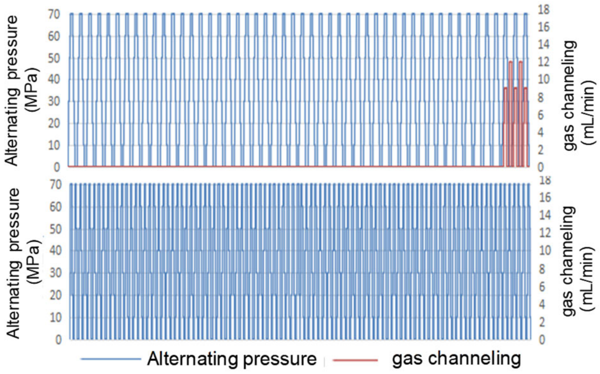

Fig. 2 Channeling flow of conventional cement and toughened cement at 105 °C and alternating stress of 70 MPa(ρ=1.90g/cm^3)

Taking the channeling flow analysis of conventional cement and toughened cement at 105 °C and alternating stress of 70 MPa as an example, the channeling comparison curve is shown in Fig. 2. The results show that :

(1)The conventional cement with elastic modulus of 9 GPa has repeated channeling after 48 times of alternating stress. At this time, the cement ring has radial and axial cracks, and the sealing failure occurs.

(2)Toughened cement with elastic modulus of 5 GPa has no channeling after more than 100 alternating stresses, and is still in a low risk state. Therefore, the simulation device can carry out the experimental analysis of cement sheath sealing in wellbore annulus, give the number of alternating stresses that different cement rings can withstand, and give the failure risk threshold under fracturing conditions.

4. Comprehensive analysis of cement sheath sealing in borehole annulus

The comprehensive analysis principle of cement ring sealing in borehole annulus is as follows: the sealing coefficient of cement ring is given by theoretical analysis, and the number of alternating stress that cement ring can withstand is given by experimental analysis. The comprehensive analysis conclusion of cement ring sealing is given by combining the two analysis. It can be seen that the sealing performance of cement sheath in borehole annulus mainly depends on the mechanical properties of cement stone, namely the cement slurry composition.

Table 2 Comprehensive analysis of cement ring sealing based on theoretical analysis and experimental analysis (70 MPa alternating stress)

temperature	Composition (ρ=1.90g/cm^3)	Theoretical Analysis	Experimental Analysis	Comprehensive Analysis
100°C	common cement	1.51	channeling after 46 times	Intermediate risk
105°C	common cement	1.51	channeling after 42 times	Intermediate risk
110°C	common cement	1.54	channeling after 48 times	Intermediate risk
100°C	Toughened Cement	1.72	Non-channeling after 100 times	Low Risk
105°C	Toughened Cement	1.77	Non-channeling after 100 times	Low Risk
110°C	Toughened Cement	1.82	Non-channeling after 100 times	Low Risk

The comprehensive analysis results show that the conventional cement with elastic modulus of 9 GPa has risk in sealing performance and certain channeling probability. Toughened cement with elastic modulus of 5GPa has low risk of sealing performance and low probability of channeling. Therefore, cement with elastic modulus less than 5GPa is recommended to prevent channeling.

5. Application of comprehensive analysis of cement sheath sealing in borehole annulus

The field test of 7 wells has been successfully carried out by using the comprehensive analysis technology of wellbore annulus cement ring sealing. The cementing qualification rate is 100 %, and there is no channeling after fracturing, which meets the long-term sealing requirements of wellbore annulus.

Table 3 Field Test Data Table of Cement Ring Sealing Comprehensive Analysis Technology in Wellbore

Well Name	Well Depth	Cement Composition	Theoretical Analysis	Experimental Analysis	Comprehensive Analysis	Cementing Quality	Channeling after Fracturing
L*-20	1674.9	Toughened Cement	1.77	Non-channeling	Low Risk	Qualify	Not occur
NAN*-54	1590.4	Toughened Cement	1.76	Non-channeling	Low Risk	Qualify	Not occur
G*-78	1919.4	Toughened Cement	1.76	Non-channeling	Low Risk	Qualify	Not occur
MAO*-S1	1868.7	Toughened Cement	1.75	Non-channeling	Low Risk	Qualify	Not occur
NAN*-45	2291.2	Toughened Cement	1.82	Non-channeling	Low Risk	Qualify	Not occur
G *-3	2366.06	Toughened Cement	1.84	Non-channeling	Low Risk	Qualify	Not occur
G *-54	2305.1	Toughened Cement	1.83	Non-channeling	Low Risk	Qualify	Not occur

6. Conclusion

(1) Based on the theoretical analysis of elastic-plastic mechanics and the experimental analysis under alternating stress, the analysis method of wellbore annulus cement sealing was established to realize the indoor analysis of wellbore annulus cement sealing.
(2) A new experimental device for the sealing of borehole annulus cement sheath was established to realize the simulation of size, working condition and continuous process, and the experimental analysis of the sealing of borehole annulus cement sheath was realized.
(3) Through the combination of theoretical analysis and experimental analysis of wellbore annulus cement ring sealing, the comprehensive analysis technology of wellbore annulus cement ring sealing is formed, which can improve the safety of wellbore annulus sealing and reduce the risk of channeling after fracturing operation.

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