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Analysis and test on stress-strain of cement sheath in shale gas wells with hydraulic fracturing

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Abstract. The sealing failure of cement sheath which caused annulus pressure in shale gas wells have significantly affected the safe and efficient development of shale gas. In view of the integrity of cement sheath which is affected by the high fluid pressure in casing during the hydraulic fracturing treatment, an experimental device for testing the integrity of cement sheath is established. In addition, the analytical model for calculating the stress and strain of the well system is established based on parameters of the experimental device. The analytical model for calculating the circumferential strain at outer wall of the steel cylinder is achieved. The error of stress-strain between analytical calculated results and the experimental results is very small. In sensitivity analysis, the parameters which affect the stress on cement sheath interface is discussed. This study has a certain reference value for the design of experiment device and the analysis of sealing ability of cement sheath in shale gas wells.

1. Introduction

The exploration and commercial development of unconventional oil and gas significantly impacts the world energy supply. In particular, the shale gas revolution in the United States has transformed it from an importer of oil and gas to an exporter [1, 2]. Horizontal well and hydraulic fracturing technology play an important role in the efficient development of shale gas. However, the sealing failure of cement sheath caused by hydraulic fracturing treatment induced serious annulus pressure buildup problems (APB) [3-5]. In the Marcellus shale gas field (United States), more than 25% of shale gas wells contains APB [6]. In Fuling shale gas field (China), 169 out of 223 production wells contains APB, and the proportion of wells with APB reaches to 75.8%. According to the statistical results of wells with APB before and after the hydraulic fracturing treatments, the proportion of wells with APB in surface casing after fracturing treatment is 39.58%, which is 11.78% higher than it before fracturing treatment. The proportion of intermediate casing with APB after fracturing treatment is 45.83%, which is 35.41% higher than it before fracturing treatment [7].

Lots of researches about the integrity of cement sheath in shale gas well have be conducted. The thermal stress is considered in calculating the stress of casing and cement sheath during the hydraulic fracturing treatment in shale gas well [8, 9]. The effect of hydraulic fracturing on the sealing ability of different types of cement sheath is studied. The elastic-ductile cement contains latex or elastic particles can significantly improve the sealing ability of cement sheath which experiences cyclic changed loads [7, 10]. Theoretical analysis and experiment method were used to study the generation and development of the micro-annulus on first and second interface due to the cyclic changed fluid pressure in casing [11, 12]. Liu et al. calculated the stress of cement sheath at the first interface and discussed the yield failure of the cement sheath [13]. Nowamooz and Guo et al. have studied the fluid channelling at casing and cement sheath interface [14, 15]. Wang et al. studied the cracks at cement sheath interface caused by hydraulic fracturing treatments. The results show that the cracks on interface is generated by high fluid pressure [16, 17].

Previous studies are mainly focusing on theoretical analysis method of channelling through annulus. But only the analytical method for the stress state of cement sheath and casing during hydraulic fracturing treatment is not enough. Based on the derived analytical method for the stress state of casing-cement sheath-formation system, an experimental device is established according to the field conditions. Ultimately, the stress and strain of the simulated casing-cement sheath-formation system is tested and analysed.

2. Experiment device

The well system composed of casing, cement sheath and formation rock. The interface between casing, cement sheath and formation rock contact well with each other. As the infinite formation rock cannot be simulated in the finite experiment device, a thick steel cylinder is used to simulate infinite formation rock. The sketch of the experimental device is shown in Figure 1.

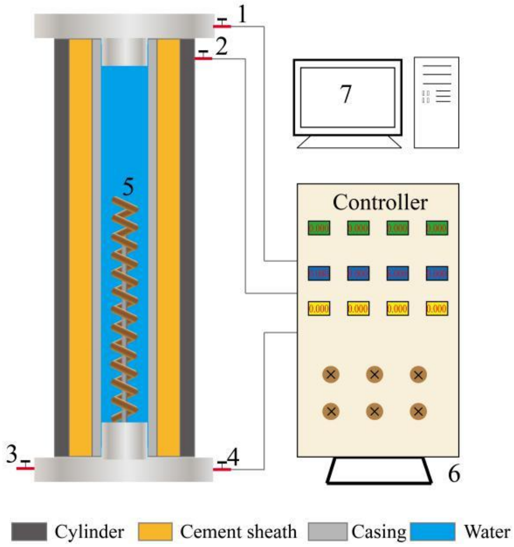


Figure 1. Sketch of the stress and strain testing device for casing-cement-formation system

In the figure: 1. Inlet for casing internal pressure, 2. Outlet for fluid in annulus; 3. Outlet for fluid in casing; 4. Inlet for fluid in annulus; 5. Heating line; 6. Controller; 7. Data acquisition and analysis device.

The actual, full size casing and annulus according to field data are used in the experiment device to simulate the field conditions. Due to the changed diameter of well wall and the different mechanical properties of formation rock, the thickness of steel cylinder should be reconsidered for each well and formation.

There are four steps to progress the experiment test. Firstly, the casing-cement-formation system should be assembled and the pipeline should be connected. Secondly, cement paste is poured into annulus and filled the annulus. Thirdly, the cement paste hardened after a certain time. Fluid is pumped into casing through the controller system and the fluid pressure in casing is increasing. At the mean time, the strain on outer wall of steel cylinder is detected through strain gage. Fourthly, after the experiment is finished, the whole experiment device should be cleared carefully.

3. Stress of casing-cement-formation system during fracturing treatment

3.1. Mechanical model

3.1.1. Calculation of radial stress on interfaces. The mechanical model for cross section the casing-cement-formation experiment device is shown in Figure 2. The inner and outer diameter of the casing is *a* and *b* respectively. The inner and outer diameter of steel cylinder is *c* and *d* respectively. The elastic modulus and Poisson's ratio of steel is E_s and v_s are. The elastic modulus and Poisson's ratio of the cement sheath is E_t and v_t respectively.

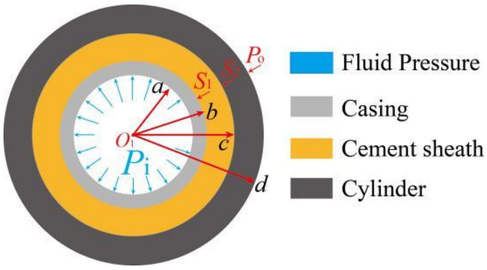


Figure 2. Mechanical model for casing-cement-formation system

Assuming that the radial stress on the first and second interface is S_1 and S_2 due to the increase of fluid pressure in casing, the radial displacement of the casing, cement sheath and steel cylinder are shown in Equation (1).

$$\begin{cases} u_r^{c} = \dfrac{1+v_s}{E_s\left(b^2-a^2\right)}\cdot\left[\left(1-2v_s\right)\left(a^2P_i-b^2S_1\right)r+a^2b^2\left(P_i-S_1\right)\cdot\dfrac{1}{r}\right] \\ u_r^{t} = \dfrac{1+v_t}{E_t\left(c^2-b^2\right)}\cdot\left[\left(1-2v_t\right)\left(b^2S_1-c^2S_2\right)r+b^2c^2\left(S_1-S_2\right)\cdot\dfrac{1}{r}\right] \\ u_r^{f} = \dfrac{1+v_s}{E_s\left(d^2-c^2\right)}\cdot\left[\left(1-2v_s\right)c^2S_2r+c^2d^2S_2\cdot\dfrac{1}{r}\right] \end{cases} \tag{1}$$

According to displacement continuity condition on the first interface, the radial displacement of outer wall of the casing equals to radial displacement of the inner wall of the cement sheath, which can be written as Equation (2).

$$\frac{1+v_s}{E_s\left(b^2-a^2\right)}\cdot\left[\left(1-2v_s\right)\left(a^2P_i-b^2S_1\right)+a^2\left(P_i-S_1\right)\right]=\frac{1+v_t}{E_t\left(c^2-b^2\right)}\cdot\left[\left(1-2v_t\right)\left(b^2S_1-c^2S_2\right)+c^2\left(S_1-S_2\right)\right] \tag{2}$$

Similarly, according to the displacement continuity condition on the second interface, the radial displacement of the outer wall of the cement sheath equals to the radial displacement of inner wall of steel cylinder, which can be written in Equation(3).

$$\frac{1+v_t}{E_t\left(c^2-b^2\right)}\cdot\left[\left(1-2v_t\right)\left(b^2S_1-c^2S_2\right)+b^2\left(S_1-S_2\right)\right]=\frac{1+v_s}{E_s\left(d^2-c^2\right)}\cdot\left[\left(1-2v_s\right)c^2S_2+d^2S_2\right] \tag{3}$$

Solving the equation (2) and equation (3), we can get the unknown S_1 and S_2, as shown in equation (4).

$$\begin{cases} S_1=\dfrac{k_{11}^{s}\left(k_{21}^{t}+k_{22}^{f}\right)P_i}{(k_{21}^{s}+k_{22}^{t})(k_{21}^{t}+k_{22}^{f})-k_{11}^{t}k_{12}^{t}} \\ S_2=\dfrac{k_{11}^{s}k_{11}^{t}P_i}{(k_{21}^{s}+k_{22}^{t})(k_{21}^{t}+k_{22}^{f})-k_{11}^{t}\cdot k_{12}^{t}} \end{cases} \tag{4}$$

Where, *k* components are used for simplification and listed as follows.

$k_{11}^{s}=\dfrac{1+v_s}{E_s}\cdot\dfrac{2\left(1-v_s\right)a^2}{b^2-a^2}$; $k_{21}^{s}=\dfrac{1+v_s}{E_s}\cdot\dfrac{\left(1-2v_s\right)b^2+a^2}{b^2-a^2}$; $k_{12}^{t}=\dfrac{1+v_t}{E_t}\cdot\dfrac{2\left(1-v_t\right)c^2}{c^2-b^2}$; $k_{22}^{t}=\dfrac{1+v_t}{E_t}\cdot\dfrac{\left(1-2v_t\right)b^2+c^2}{c^2-b^2}$;

$k_{11}^{t}=\dfrac{1+v_t}{E_t}\cdot\dfrac{2\left(1-v_t\right)b^2}{c^2-b^2}$; $k_{21}^{t}=\dfrac{1+v_t}{E_t}\cdot\dfrac{\left(1-2v_t\right)c^2+b^2}{c^2-b^2}$; $k_{12}^{f}=\dfrac{1+v_f}{E_f}\cdot\dfrac{2\left(1-v_f\right)d^2}{d^2-c^2}$; $k_{22}^{f}=\dfrac{1+v_f}{E_f}\cdot\dfrac{\left(1-2v_f\right)c^2+d^2}{d^2-c^2}$ 。

3.1.2. Circumferential strain at outer wall of steel cylinder. According to Equation (4), the stress on second interface can be calculated. The circumferential strain at inner and outer wall of steel cylinder are

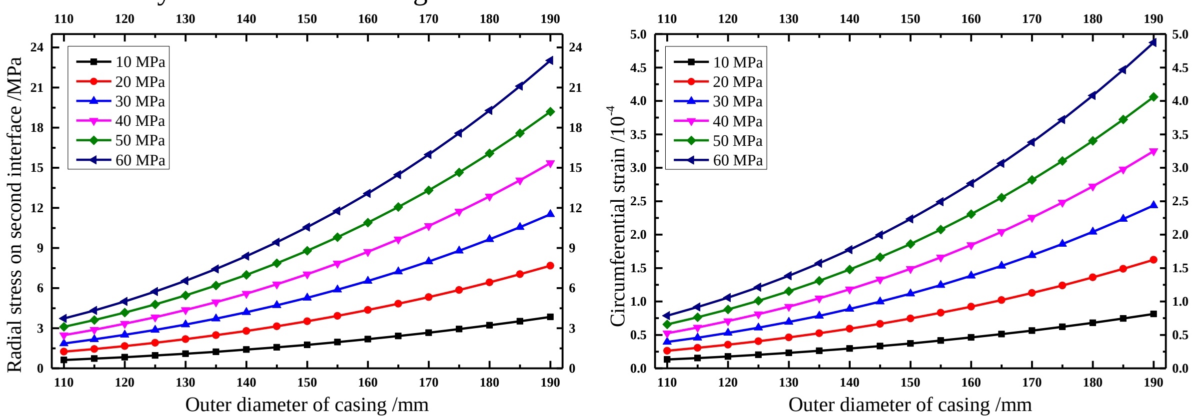
$$\begin{cases} \varepsilon_\theta^{r=c} = \dfrac{(1+v_s)\left[(1-2v_s)c^2+d^2\right]}{E_s\left(d^2-c^2\right)}\cdot S_2 \\ \varepsilon_\theta^{r=d} = \dfrac{(1+v_s)(2-2v_s)\cdot c^2}{E_s\left(d^2-c^2\right)}\cdot S_2 \end{cases} \tag{5}$$

3.2. Sensitivity analysis

The radial stress on the first and second interface of well system is mainly affected by five parameters: casing outer diameter, casing thickness, well diameter, elastic modulus of cement sheath and elastic modulus of formation rock. In which, the first four parameters can be designed and optimized according to the field requirements. The elastic modulus of formation rock is an inherent property and it cannot be changed, but it affects the thickness of cylinder used in the experimental device. Therefore, in this section, the effects of five parameters on the radial stress at second interface and the strain on outer wall of cylinder in experimental device is discussed.

Basic data in the calculation are listed as follows. The well diameter is 215.9mm, elastic modulus of formation rock is 45GPa, elastic modulus of cement sheath is 8GPa, thickness of casing is 10mm, and the outer diameter of casing is 139.7mm. The fluid pressure in casing is set as 10MPa, 20MPa, 30MPa, 40MPa, 50MPa and 60MPa respectively. In each sensitivity analysis, only the discussed parameters is changeable and the other parameters are in constant.

3.2.1. Outer diameter of casing. The effects of casing outer diameter on the radial stress at second interface and the circumferential strain at outer wall of cylinder are calculated. The outer diameter of casing ranges from 110mm to 190mm. The thickness of cement sheath changes with the varied casing outer diameter if the diameter of well wall is in constant. With the change of outer diameter of casing, the calculated radial stress at second interface are shown in Figure 4a and the circumferential strain at outer wall of cylinder is shown in Figure 4b.

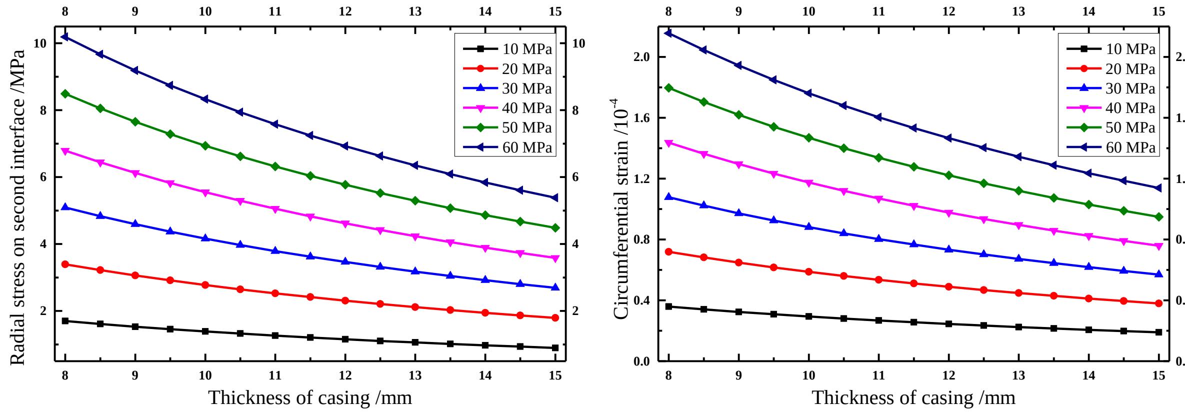


a b

Figure 4. Change of radial stress on interface II and circumferential strain on cylinder with casing outer diameter

It can be seen from Figure 4a that the radial stress at the second interface increases non-linearly with the increase of casing outer diameter. The higher fluid pressure in casing caused the larger and faster increase of radial stress at the second interface. The larger casing outer diameter causes the faster increase of radial stress at second interface. If the outer diameter of casing equals to 139.7mm and the fluid pressure in casing equals to 60MPa, the radial stress at second interface reaches to 15.2MPa. When the outer diameter of casing increases from 190mm to 110mm, the radial stress at second interfaces increase by 6.18 times. The variation rule of circumferential strain at outer wall of cylinder is similar to the radial stress at second interface. When the outer diameter of cylinder equals to 190mm, the circumferential strain at outer wall cylinder reaches 0.0005.

3.2.2. Thickness of casing. The effect of thickness of casing on the radial stress at second interface and the circumferential strain of cylinder is calculated. The thickness of casing ranges from 8mm to 15mm. With the change of thickness of casing, the calculated radial stress at second interface are shown in Figure 5a, and the circumferential strain at outer wall of cylinder is shown in Figure 5b.

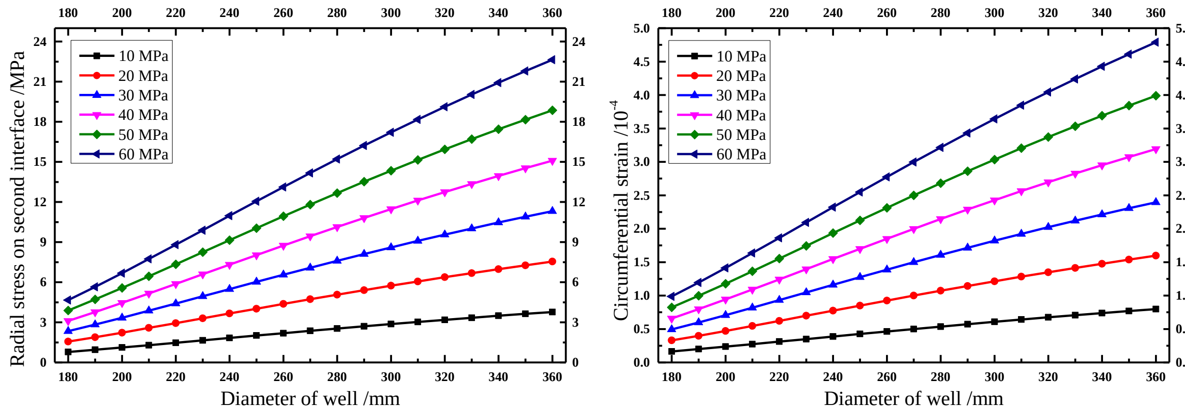


a b

Figure 5. Change of radial stress on interface II and circumferential strain on cylinder with casing thickness

The thicker casing leads to the lower radial stress at second interface. A thinner casing caused the faster change of radial stress at interface. When the fluid pressure in casing equals to 60MPa and thickness of casing equals to 8mm, the radial stress at second interface is 10.2MPa, which is 1.89 times of the radial stress at second interface when thickness of casing equals to 15mm. It can be seen that the effect of outer diameter of casing on radial stress at second interface is much more serious than thickness of casing. When the thickness of casing is 8mm and the fluid pressure is 60MPa, the circumferential strain at outer wall of cylinder is 0.0002.

3.2.3. Diameter of well. The effect of diameter of well wall on the radial stress at second interface and the circumferential strain of cylinder is calculated. The diameter of well wall ranges from 180mm to 360mm. With the change of diameter of well wall, the calculated radial stress at second interface are shown in Figure 6a, and the circumferential strain at outer wall of cylinder is shown in Figure 6b.

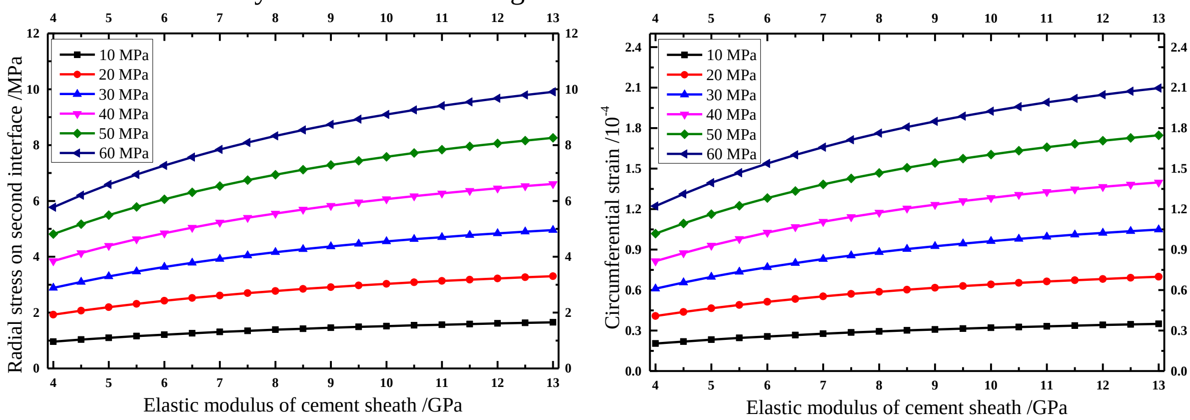


a b

Figure 6. Change of radial stress on interface II and circumferential strain on cylinder with well diameter

It can be seen from Figure 6a that the radial stress at second interface increases linearly with the increase of well diameter. If the fluid pressure in casing is 60MPa, the radial stress on interface is 22.4MPa when the well diameter equals to 360mm, which is 4.85 times of the value when well diameter equals to 180mm. For the shale gas well with diameter of well wall equals to 215.9mm, the radial stress at second interface reaches 8.28MPa. The circumferential strain at outer wall of cylinder changes rapidly with the diameter well wall, and it increases from 0.000098 to 0.0005 when the diameter of well wall increasing from 180mm to 360mm.

3.2.4. Elastic modulus of cement sheath. The effect of elastic modulus of cement sheath on the radial stress at second interface and the circumferential strain of outer wall of cylinder is calculated. The elastic modulus of cement sheath ranges from 4GPa to 13GPa. With the change of elastic modulus of cement sheath, the calculated radial stress at second interface are shown in Figure 7a, and the circumferential strain at outer wall of cylinder is shown in Figure 7b.



a b

Figure 7. Change of radial stress on interface II and circumferential strain on cylinder with elastic modulus of cement sheath

The change of elastic modulus of cement sheath has little effect on the radial stress at the second interface. According to the previous research [13], the change of elastic modulus of cement sheath mainly affects the circumferential stress of cement sheath, which is of great significance for controlling the integrity failure of cement sheath. For studying the radial stress at the second interface, the effect of other parameters should be considered in the optimization design. When the fluid pressure in casing is 60MPa, and the radial stress at interface increased by 1.71 times higher when the elastic modulus of cement sheath increases from 4GPa to 13GPa. The variation trend of circumferential strain on outer wall of cylinder is in the same of radial stress on interface.

3.2.5. Elastic modulus of formation rock. The effect of elastic modulus of formation rock on the radial stress at second interface and the circumferential strain of cylinder is calculated. The elastic modulus of formation rock ranges from 10GPa to 80GPa. According to the relationship between the elastic modulus of formation rock and the thickness of cylinder, the thickness of outer cylinder ranges from 13.08mm to 43.19mm. With the change of elastic modulus of formation rock, the calculated radial stress at second interface are shown in Figure 8a, and the circumferential strain at outer wall of cylinder is shown in Figure 8b.

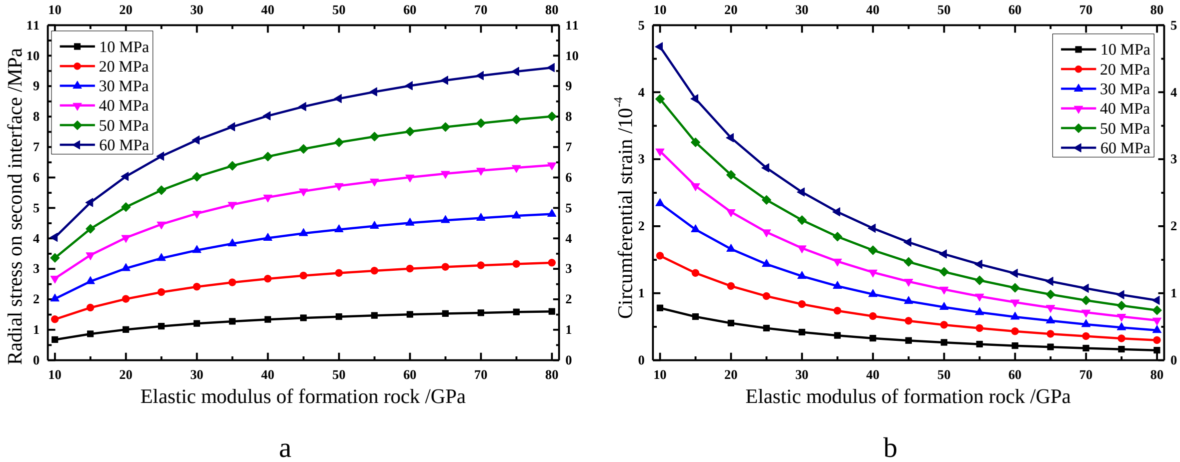


Figure 8. Change of radial stress on interface II and circumferential strain on cylinder with elastic modulus of formation rock

It can be seen from Figure 8a that with the increase of elastic modulus of formation rock, the radial stress at second interface is increasing. But the effect of elastic modulus of formation rock on radial stress at second interface is insignificance. When the elastic modulus of formation rock increases from 10GPa to 80GPa, the radial stress at second interface increases by 2.38 times of the value when elastic modulus of formation rock equals to 10GPa. The variation trend of the circumferential strain at outer wall of cylinder is in opposite with the variation trend of radial stress at interface. The larger elastic modulus of formation rock leads to smaller circumferential strain. Due to the increase of elastic modulus, the thicker experimental cylinder will be used, which can reduces the circumferential strain at outer wall of cylinder. When elastic modulus equals to 80GPa, the circumferential strain is just 0.19 times of the train when elastic modulus equals to 10GPa.

4. Experimental test

As it is difficult to measure the strain on casing or cement sheath, fiber-optic sensor is used to measure the circumferential strain at outer wall of cylinder caused by the increased fluid pressure in casing. The experimental device is shown in Figure 9. The Figure 9a is controlling system which can provide loads from the loading device and test the gas flow at the inlet and outlet of annulus. The Figure 9b is test system which consists of casing-cement-formation simulation system and strain test system. The casing-cement-formation simulation system provide the true well size. The strain test system is used to test the strain in steel cylinder during the loading and unloading in casing. The geometric parameters and material properties for the experimental device are shown in Table 1. The experimental results are shown in Figure 10. In addition, based on the parameters in Table 1, the theoretical calculation method in this paper is used to calculate the circumferential strain at outer wall of the cylinder with different fluid pressure in casing. The calculated results are also shown in Figure 10.

Table 1. Parameters for the experiment device

	Dimensions		Properties	
	OD（mm）	Thickness（mm）	Elastic modulus（GPa）	Poisson ratio
Casing	139.70	7.72	210	0.3
Cement sheath	193.10	26.70	10	0.25
Cylinder	244.5	25.7	210	0.3

Figure 9. Experiment device for testing integrity of cement sheath according to field data

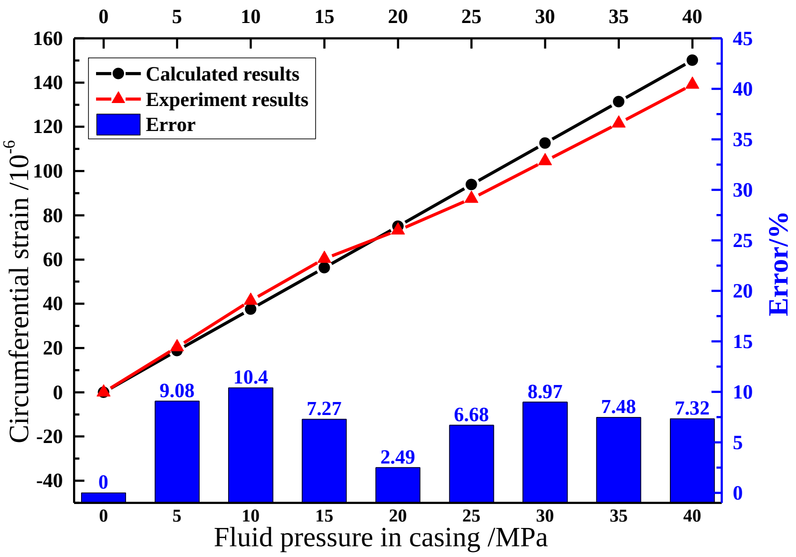


Figure 10. Comparison of the strain from experiment and theoretical analysis methods

It can be seen from Figure 10 that the circumferential strain increases linearly with the increased fluid pressure in casing. When the fluid pressure in casing equals to 20MPa, the error between experiment and calculated results is only 2.49%. When the fluid pressure in casing equals to 5MPa, the calculated circumferential strain at outer wall of the outer casing is 20.5×10^{-6}. It is in an error 9.08% compared with the experimental results. When the fluid pressure in casing equals to 20MPa, the circumferential strain at outer wall of cylinder is 73.19×10^{-6}. When the fluid pressure in casing equals to 40MPa, the circumferential strain at outer wall of cylinder is 139.13×10^{-6}, and the error is 7.32%.

The theoretical calculated results are smaller than the experiment values when the fluid pressure in casing is lower than 20MPa. But on the contrary, the theoretical calculated results are larger than the experiment results when the fluid pressure in casing is higher than 20MPa. This phenomenon is mainly due to the cellular structure in cement sheath. When the stress in cement sheath is larger than its strength, the plastic deformation occurs, like collapse of micropore in cement sheath, and ultimately, the radial stress acts on inner wall of steel cylinder will be lowered by plastic deformation in cement sheath. So in the comparison, the calculated results is larger than experiment results when the fluid pressure in casing is higher than 20MPa.

According to the comparison of calculated results with experimental results, we can see that the calculated results from theoretical method established in this paper is close to the experimental results. It verifies the correctness of the analytical calculation method in this paper. The results show that the thickness cylinder (the elastic modulus of formation rock) has a great influence on the circumferential strain of cylinder, so it is important to make a good design the thickness of the cylinder in the experimental device according to the property of different formation rock. A new cement formulation which is planed to be used in a well, the sealing ability of can be calculated and tested through the method in this paper and the results can provide reference value for field application. It also can help optimizing the cement formulation to increasing the performance of cement sheath.

5. Conclusions

Analytical model for calculating the stress and strain on second interface is established and the radial stress at the second interface of cement sheath is calculated. In addition, experiment device for testin the strain at outer wall of steel cylinder is built and the varied circumferential strain on the outer wall experimental cylinder caused by the change of fluid pressure in casing is tested in this paper. Through the research in this paper, some conclusions are are achieved.

(1) The effect of each parameter on the radial stress on interface is different. The larger outer diameter of casing and well wall can induced higher radial stress at second interface. But the thicker casing can caused lower radial stress. Elastic modulus of cement sheath has little effect on radial stress and strain at second interface.

(2) Although a larger elastic modulus of formation rock may lead to higher radial stress at second interface, the circumferential strain at well wall will be smaller. It is necessary to optimize the design of each parameter according to the field requirement, so as to meet the needs of the sealing ability of the cement sheath in wells.

(3) Experiment study on stress and integrity of cement sheath is very important and useful. The error between the calculated results and the experimental results is small, which both proves the accuracy of the simplified casing-cement sheath-formation rock analytical model and the reliability of the experimental device. But when the fluid pressure in casing is higher than 20MPa, the calculated results is higher than experiment results. It may be caused by the plastic deformation due to the collapse of micropore in cement sheath. More attention should be paid on this phenomenon in the future. The analytical and experimental method is useful for the optimized design of casing and cement sheath before well completion.

6. Acknowledgments

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7. Reference

[1] Wang Lin, Ma Jinliang, Su Fengrui, et al., 2012, Shale gas factory fracturing technology in North America.D*rilling & Production Technology,* 35(06):48-50.

[2] Liu Shuchen, Yan Weidong, 2012, The current situation and Enlightenment of shale gas exploration and development in the world. *Guo Tu Zi Yuan Qing Bao*, 02: 2-6.

[3] Gao Deli, Liu Kui. 2019, Progresses in shale gas well integrity research. *Oil & Gas Geology,* 40(3): 602-615.

[4] Chen Lei, Chen Huinian, Zhang Linhai, et al., 2019, A cementing technology for preventing the annulus pressure of horizontal wells in JY shale gasfield. *Oil Drilling & Production Technology*, 41(2): 152-159.

[5] Song Jianjian, Chen Xiaolong, Xu Mingbiao, et al.,2019, Analysis of the difficulties in prevention and control of annular pressure in shale gas wells. *Drilling & Production Technology*, 42(02): 32-35+2.

[6] R W H, K K D, F. K R., 2011, Flexible, expanding cement system (FECS) successfully provides zonal isolation across Marcellus shale gas trends: Canadian Unconventional Resources Conference. *Society of Petroleum Engineers.*

[7] Tao Qian, Chen Xingxing, 2017, Causal analysis and countermeasures on b sustained casing pressure of shale-gas horizontal wells in the sichuan basin.*Oil Drilling & Production Technology*, 39(05):588-593.

[8] Xi Yan, Liu Gonghui, Li Jun,et al., 2017,Study on Casing Transient Stress under Thermo-mechanical Coupling Effect.*China Petroleum Machinery*, 45(06):8-12.

[9] Xi Yan, Li Jun, Liu Gonghui, et al., 2019, Research into cement sheath integrity during multistage hydraulic fracturing in shale gas wells. *Petroleum Science Bulletin*, 01: 57-68.

[10] Zhang Linhai, Liu Rengguang, Wang Chong., 2017, Investigation on sealing failure and improving of cement sheath under simulated staged fracturing[J].*Science Technology and Engineering*, 17(13):168-172.

[11] Liu Shuoqiong, Li Deqi, Yuan Jinping, et al., 2017, Cement sheath integrity of shale gas wells:A case study from the Sichuan Basin.*Natural Gas Industry*, 37(07):76-82.

[12] Liu Rengguang, Zhang Linhai, Tao Qian, et al., 2016, Experimental Study on Airtightness of Cement Sheath Under Alternating Stress. *DFCF*, 33(4): 74-78.

[13] Liu Kui, Wang Yanbin, Gao Deli,et al., 2016, Effects of hydraulic fracturing on horizontal wellbore for shale gas[J].*Acta Petrolei Sinica*, 37(03):406-414.

[14] A N, M L J, J M, et al., 2015, Numerical investigation of methane and formation fluid leakage along the casing of a decommissioned shale gas well. *Water Resources Research*, 51(6):4592-4622.

[15] Guo Xinyang, Bu Yuhuan, Shen Zhonghou, et al., 2010, The effect of downhole complex temperature conditions on the interfacial bonding strength in cementing. *Acta Petrolei Sinica*, 31(5): 834-837.

[16] Wang W., Dahi Taleghani A., 2014, Cement Sheath Integrity During Hydraulic Fracturing; An Integrated Modeling Approach: Society of Petroleum Engineers., *SPE Hydraulic Fracturing Technology Conference*, 4-6 February, The Woodlands, Texas, USA.

[17] Li Yong, Chen Yao, Jin Jianzhou, et al., 2017, Cement ring interface crack propagation under volume fracturing in shale gas well. *Acta Petrolei Sinica*,38(01):105-111.