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Analysis and countermeasures on sustained casing pressure in b-annulus of shale-gas horizontal wells in Sichuan basin of china

Abstract

In Sichuan Basin of China, the percentage of shale gas wells with sustained casing pressure (SCP) is high, bringing about challenges to the efficient development of gas reservoirs and the wellbore integrity of gas wells. In this paper, the actual SCP situa¬tions in domestic shale gas development blocks were analyzed specifically. The gas source was determined by using the isotope analysis method, and SCP mechanisms of shale gas wells were studied by means of physical simulation experiment. Accordingly, the failure laws of cement sheath in different cement slurry systems in the process of fracturing were figured out, and the key technologies of improve the sealing capacity of cement sheath and relieve the SCP phenomenon in staged fracturing wells were developed. On the premise that the cement slurry column can structurally satisfy the sealing requirement completely, a cement slurry system of low porosity and low elastic modulus was developed by means of the interphase filling technique and the set cement porosity decreasing method. The elastic modulus was only 4.2 GPa, the porosity was as low as 27.1% (the porosity of conventional cement stone is 35.0%), and the elastic deformation capacity of cement stone was en¬hanced dramatically. The new cement slurry system has been practically applied in 5 wells, and the high-quality cementing rate was 100% with no SCP. This research provides useful reference for SCP control.

Keywords: sustained, casing, pressure, shale gas well, cementing, slurry, staged, fracturing

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Introduction

The success of shale gas exploration and development is of great significance to the world's energy restructuring. Fuling shale gas field is the first shale gas development demonstration area in China. By the end of 2015, the 1st phase of 5 billion m^3 production capacity building had been completed, and it is planned to build it into a gas field of 10 billion m^3 at the end of the "Thirteenth Five-Year Plan" period; however, along with the continuously deepened exploration and development, SCP appeared in several wells of No.5 and No.26 gas production platforms, and other wells like N209, N210 and N203 in Weiyuan shale gas demonstration area also experienced various degrees of SCP, bringing a certain impact to long-term production safety.[1] Based on the specific analysis of the actual situation of SCP in shale gas fields, and by means of determining the gas sources through isotopic analysis, this paper adopted physical simulation test method to study the SCP mechanism of shale gas wells, clarified the cement sheath sealing failure laws of various cement slurry systems during fracturing, and formed the key technologies of improving the sealing performance of the cement sheath and alleviating SCP phenomenon in staged fracturing wells. The technologies mentioned above have been field applied in five wells, achieving the high quality rate of cementing quality of 100 %, and up to now, no SCP phenomenon has occurred, which provides an important reference for later shale gas well cementing engineering.

Analysis on the SCP characteristics of shale gas wells

Currently, the favorable exploration and development blocks of the shale gas in Southern China are mainly located in Chongqing and Sichuan, and the target layer is Longmaxi shale formation, with the reservoir depth of 2800-4000m. The development wells adopt the third-spud casing program and use staged fracturing technology to stimulate the shale reservoirs. Analysis was conducted on wells being produced in a demonstration area on the southeast edge of Sichuan Basin. In order to further clarify the SCP situation in this block, the characteristics of wells with SCP were specifically analyzed:

a) wells of which the annulus between technical casing and production casing (annulus B) having pressure of over 30 MPa only accounted for 0.88% of the total wells with SCP; wells showing SCP of 20-30MPa accounted for 15.93%; wells showing SCP of 10-20MPa accounted for 23.89%, and wells showing SCP of less than 10-20MPa accounted for 59.29%; however, gas escape at wellhead cellar occurred in some wells, bringing about hidden hazards to safe production.

b) From the aspect of the SCP period, the occurrence of SCP has significantly intensified after staged fracturing: wells showing SCP in annulus B before fracturing accounted for 19.04% of the total wells with SCP, and after fracturing, such proportion reached up to 63.70%, having an increase of 44.64%. Meanwhile, along with the increase of production time, the proportion of wells with SCP increased year by year. As for the wells being put into production within one month, SCP was observed in 19.14% of the wells. Two months later, it was observed in 5.07% of the wells; three months later, it was observed in 7.23% of the wells, and three years later, it was observed in 4.87% of the wells. The results show that fracturing has a great influence on the cement sheath sealing ability of shale gas wells.

Causal analysis on the SCP of shale gas wells

The cement sheath annulus seal is affected by many factors, mainly including

a) geological and reservoir factors: e.g., poor interface cementation caused by leakage, and cement stone strength decline under high temperature

b) drilling factors: e.g., wellbore geometry and poor drilling fluid performance, low displacement efficiency, poor cementing quality, etc

c) cementing factors: poor performance of cement slurry, mechanical properties of cement stone failing to meet long-term sealing requirements

d) Development factors: temperature and pressure changes in wellbore caused by fracturing, workover, and production adjustment, etc.

Further affecting the sealing ability of cement sheath.[2,3] By using the isotope measurement and physical model research methods, and combined with the actual site parameters of Jiaoshi dam, mechanism analysis on gas sources and the specific causes of SCP were conducted.

Analysis on gas sources

In the shale gas wells in a demonstration area on the southeastern margin of Sichuan Basin, hydrocarbon shows are observed in the following layers: Changxing formation, Maokou formation, Qixia formation, and Longmaxi formation. The cementing layer of technical casing is the intervals above Longmaxi turbidite sandstone, and the cementing layer of production casing is Longmaxi formation. In order to accurately determine the gas source in the annulus, $\delta^{13}C_{PDB}$ measurement and evaluation method was used to conduct CH_4 isotope analysis on wellhead produced gas samples, annular C (the annulus between surface casing and technical casing) and annulus B (the annulus between technical casing and production casing) of 3 wells with SCP. The isotope analysis of CH_4 is shown in Table 1. The measured $\delta^{13}C_{PDB}$ value of produced gas (that is, the gas entering the pipe network from the separator) was−31.52, which was similar to that of the gas samples from annulus B of wells F7-1HF, F7-2HF, and F20-2HF; however, it was distinctively different from the test value (-52.08) of gas samples from annulus C in Well F7-1HF. In terms of the differences in the forming conditions and time of methane gas, the test results showed that the gas source in annulus C was derived from shallow gas, and the gas source in annulus B was mainly derived from Longmaxi formation. Therefore, preliminary judgment can be made that the SCP in annulus C was caused by the failure of cement sheath seal in annulus C.

Causal analysis on SCP of production casing

Currently, the methods for analyzing the integrity of cement sheath with SCP are mainly numerical calculations and numerical simulations, most of which using elasticity theory and thick-walled cylinder theory to start the analysis and calculations. However, numerical simulation analysis has a relatively simple characterization on the assumption of boundary conditions and the mechanical behavior of cement stone, which cannot actually reveal the mechanism of cement sheath seal failure.[2,3] In order to further clarify the reason for SCP in annulus C, a full-scale cement sheath sealing capacity evaluation device was used to conduct physical simulation tests. The basic principle of the device is: casing, cement sheath and outer cylinder are used to simulate the casing-cement sheath-formation assembly, and then pressure system is used to load and unload the casing to simulate the load variations of casing and cement sheath during the fracturing process. During this process, air bubble detection and gas flow rate test can also be performed to realize the engineering restoration of shale gas wells with SCP. The casing with the same quality of that for shale gas well completion in the demonstration area was selected for the test. Such casing has an outer diameter of 139.7mm, steel grade of P110, and cement sheath wall thickness of 26.7mm. At the same time, a metal alloy cylinder with wall thickness of 22.5mm and outer diameter of 244.5mm was used to simulate the shale formation with elastic modulus of 25.0 GPa and Poisson's ratio of 0.18. The overall length of the model is 1000mm, and the physical device is shown in Figure 1. Aimed at the conventional cement slurry, latex cement slurry system, and toughening cement slurry currently widely used in this area, the sealing ability of cement sheath during the staged fracturing simulation was evaluated. The cement stone was cured at 80°C for 7 days. The measured uniaxial compressive strength of the conventional cement stone was 35.5MPa, the straight resistance strength was 3.5MPa, and the elastic modulus was 14.3GPa; the compressive strength of the latex cement slurry was 24.5MPa, the straight resistance strength was 3.2MPa, and the elastic modulus was 8.2GPa; the compressive strength of toughening cement slurry was 35.7MPa, the straight resistance strength was 4.3 MPa, and the elastic modulus was 9.4 GPa. Pressurize the casing with 70MPa to simulate the fracturing job, and perform several cycles of loading and unloading to simulate the staged fracturing process. The pressure curves and gas channeling curves under the action of loading and unloading are shown in Figure 2 to Figure 4. The experimental results show that in the test of 3 samples of conventional cement stone, gas channeling was detected separately after the unloading of the 1st loading and unloading cycle in the 1st test, the 2nd loading and unloading cycle in the 2nd test (Figure 2), and the 2nd loading and unloading cycle in the 3rd test. As for the latex cement slurry, deterioration was detected separately at the 15th cycle in 1st test, the 14th cycle in the 2nd test (Figure 3), and the 14th cycle in the 3rd test; a gap of over 0.01mm was observed,[4] and gas channeling began to occur. As for toughening cement slurry, gas channeling was detected after the unloading of the 11th cycle (Figure 4).

Figure 1 Photo of large physical simulation device for sealing capacity of cement sheath.

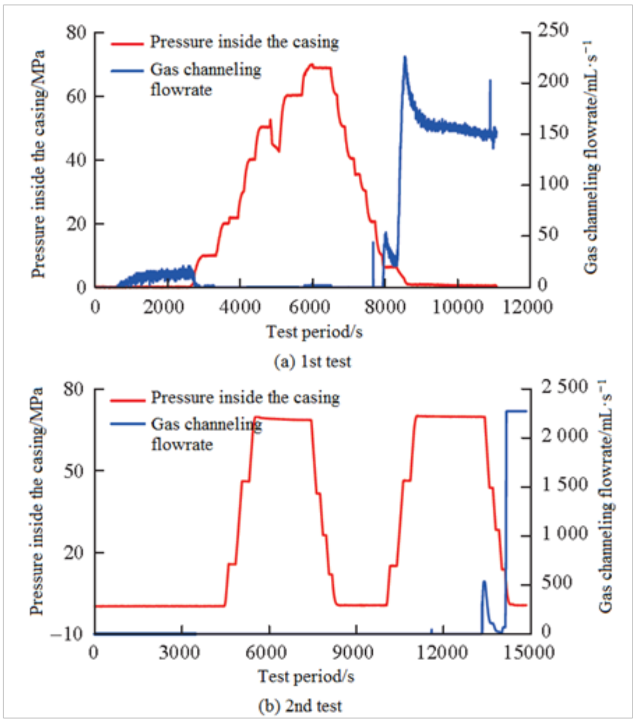

Figure 2 Analysis on the gas channeling in the loading and unloading process of conventional cement slurry.

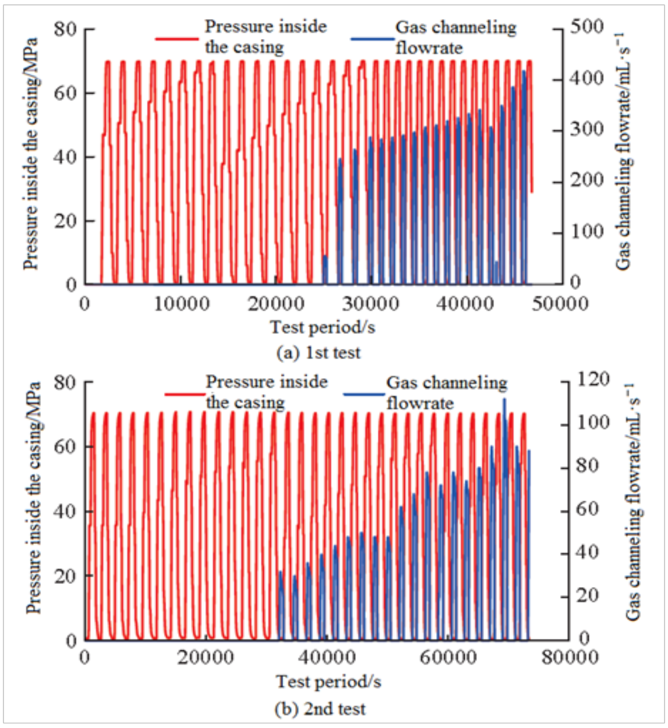

Figure 3 Analysis on the loading and unloading of latex cement slurry.

Meanwhile, the acoustic characteristics during cement sheath seal failing were monitored using acoustic emission technology: a large number of signals were received at the initial loading of the conventional cement stone, the 4-7th cycles of loading and unloading, and the 20th cycle of loading and unloading. The signal type showed that the rock was vulnerable to brittle deformation, and the damage of cement stone was severe during these cycles of loading and unloading. During the initial and first three cycles of loading and unloading for latex cement slurry system, the acoustic emission signal was weak, and from the 4th cycle to the end, the acoustic emission signal was stable, which showed that the rock was destructive to plastic deformation.

Through the mechanical monitoring on the stress state of cement sheath during loading, it was found that due to the high modulus of conventional cement stone, the cement sheath experienced high circumferential tensile stress caused by the expansion of casing under the condition of external load; the tensile stress reached up to 4.2MPa (Figure 5), tensile cracks were formed **(**Figure 6) and thus cement sheath seal failure occurred. As for cement sheath formed by latex cement slurry, under cyclic loading and unloading conditions, cement stone was not mechanically damaged, and plastic failure was the key factor of cement sheath seal failure (Figure 7). Cyclic loading was applied to the cement stone, and the tested cumulative effect of cement stone plastic deformation is shown in Figure 8. Due to the accumulation of plastic deformation, the cementation of the first interface and second interface of cement sheath deteriorated, an annulus gap was formed and thus SCP occurred.

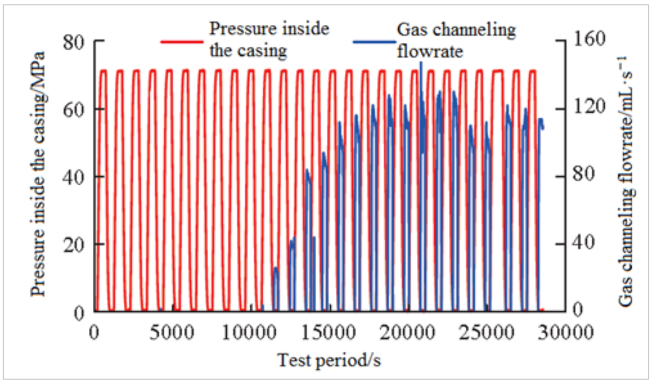

Figure 4 Analysis on the loading and unloading of tough cement slurry.

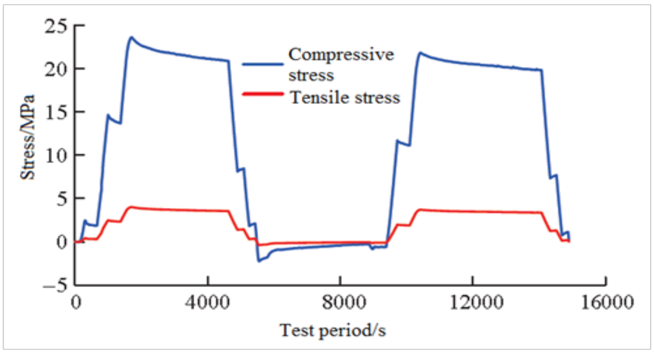

Figure 5 Interfacial stress in the loading process of conventional cement stone.

Countermeasures and implementation

Prevention of production casing SCP

The experimental study on the failure of cement sheath seal during staged fracturing suggested that the hard-brittleness and the accumulation of plastic deformation of cement stone led to the failure of cement sheath seal. Therefore, improving the hard-brittleness of cement stone and increasing the deformability of cement stone can effectively relieve SCP phenomena. The improvement of hard-brittleness of cement stone and the enhancement of cement stone deformability are mainly realized through the plasticization of crystalline phase, the plasticization of gel phase and the filling of cement stone matrix. Meanwhile, in order to effectively reduce the plastic deformation of cement stone, it is necessary to reduce the porosity of cement stone effectively and restrain the microscopic and macroscopic defects of cement stone.[5-10]

A low elastic modulus and low porosity cement slurry system was designed, with the basic formula as follows: JHG+(2-8)% organic elastic material+(8-15)% non-base nanoemulsion+(2-3) % fluid loss additive+(2-3)% expansion agent+(0.1-0.5)% retarder+(1-2)% non-base toughener+44% water. The density of cement slurry formed was 1.88g/cm^3, the permeability of cement stone was 0.02mD, and the porosity was 25.5%-27.8%, which was 27.1% lower than that of the conventional cement stone; the API water loss was less than 36 mL, the free fluid was 0, the 48 h compressive strength was greater than 12 MPa, and the initial consistency was less than 22Bc. The mechanical properties of cement stone are shown in Figure 9. The dosage of elastic material was 2%-8%, and the elastic modulus of cement stone was 4.2-7.5GPa. When the dosage of elastic material was more than 6%, the elastic deformation range of cement stone reached up to 75% of the uniaxial compressive strength, and its elastic deformation capacity was basically good. The cumulative plastic deformation under cyclic load was reduced by 28.5% comparing with the conventional cement stone. Under 70MPa staged fracturing condition, the number of loading cycles for cement sheath reached up to 35 times, meeting the current requirements for staged fracturing of all wells in Jiaoshiba area.

Figure 6 Damage form in the loading process of conventional cement set.

Field implementation

The slurry column structure used in the shale gas demonstration area on the southeastern edge of Sichuan Basin was a two-stage slurry column; the conventional cement slurry was used as the lead slurry, and latex cement slurry was used as the tail slurry. Due to the influence of staged fracturing, the conventional cement stone was vulnerable to brittle failure. Since the brittleness of latex cement stone was not completely modified, the cement stone still had a high modulus of elasticity, which resulted in the failure of cement sheath seal during fracturing process. Therefore, in order to effectively improve the sealing ability of the cement sheath after staged fracturing, a whole-wellbore high gas sealing performance slurry system shall be used in the slurry column structure design.

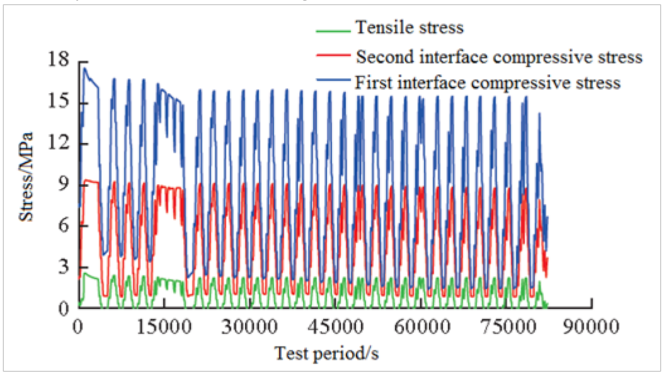

Figure 7 Interfacial stress in the loading process of latex cement set.

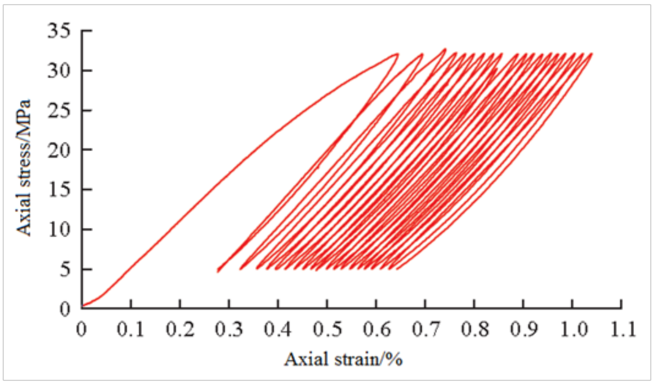

Figure 8 Plastic deformation of cement set under cyclic loading.

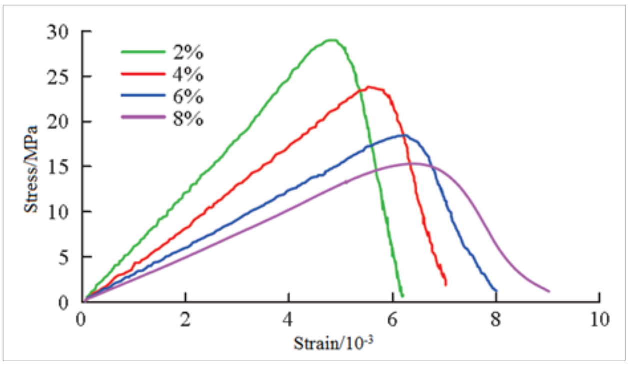

Figure 9 Stress and strain of cement stone with different dosages of elastic materials.

The newly developed low-porosity and low-elastic-modulus elastic cement slurry system has been applied in 5 wells. The cementing quality was excellent, and no SCP phenomenon occurred in test or production. The application results are shown in Table 2. The results indicate that the use of a whole-wellbore high-performance slurry system and a reasonable slurry column structure can effectively improve the long-term sealing capability of the cement sheath, relieve SCP phenomenon, and ensure the safe production of shale gas wells after staged fracturing.

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Table 1 Isotope analysis on annulus gas

Well number	Sampling position	$\delta^{13}C_{PDB}$/‰	Gas source
F7-1HF	Separator (produced gas)	-31.52	Target layer
F7-1HF	Annulus C	-52.08	Shallow layer
F7-1HF	Annulus B	-31.49	Target layer
F7-2HF	Annulus B	-31.52	Target layer
F20-2HF	Annulus B	-31.11	Target layer

Table 2 Field implementation and application

Well number	Number of stages	Max fracturing pressure/MPa	Production period/year	Cementing quality	Dosage of elastic material/%	Elastic modulus/ GPa	SCP
J1-2HF	18	85.0	3	Excellent	6	4.5	No
D2HF	16	115	2.5	Excellent	8	3.2	No
LY1-HF	18	87.0	1.5	Excellent	6	4.5	No
PY2-HF	25	82.5	4.0	Excellent	6	4.5	No
PY3-HF	22	83.0	3.8	Excellent	6	4.5	No

Conclusion

The results of isotopic analysis showed that the gas sources in the annulus between technical casing and production casing were Longmaxi shale gas. The main reason of SCP was the effect of staged fracturing on the sealing ability of cement sheath. A large number of physical simulations and indoor evaluations suggested that during staged fracturing, the body damage of conventional cement stone led to a decrease in the sealing ability of cement sheath. The main reasons for failure of latex cement sheath seal were the accumulation of cement sheath plastic deformation and the eventually formed annulus gap, which led to SCP. Improving the mechanical properties of cement stone can effectively reduce the elastic modulus of cement stone, narrow the elastic deformation range of cement stone, and reduce plastic deformation, thus improving the sealing ability of cement sheath. Adopting a whole-wellbore high efficient sealing performance slurry column structure in shale gas wells to optimize the lead slurry performance is one of the key technologies of effective SCP control.

Acknowledgements

None.

Conflicts of interest

The author declares that there is no conflict of interest.

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