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Research Article

# Cement sheath integrity of shale gas wells: A case study from the Sichuan Basin

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**Abstract**

Sustained annulus pressure and casing deformation of gas wells are common in several shale gas demonstration areas in the Sichuan Basin. In view of this, the conditions for pressure change inside the wellbore in the process of drilling were analyzed, and then an elastic–plastic mechanical model of casing–cement sheath–surrounding rock system for calculating the whole change process of wellbore pressure in the stress–strain state was established. By virtue of this model, the generation and development of micro-annulus at the first and second interfaces under various internal pressure conditions were analyzed. Then, combined with the actual field data, calculation was performed. Results show that no micro-annulus is generated in the process of loading, but the loaded internal pressure determines the plastic deformation degree of cement sheath. Besides, the decrease of internal pressure during the unloading exerts tension on the interface, leading to the generation of micro-annulus, and consequently the integrity of cement sheath is damaged. Finally, the mechanical performance of cement sheath can be improved by optimizing the slurry formula, and operation technologies are used to guarantee the integrity of cement sheath in shale gas wells. This model was applied in 13 wells for field tests. It is indicated that the average good quality rate of horizontal section cementing is 92.67%, and 11 wells which have been put into production are not subjected to sustained annulus pressure. It is demonstrated that the sustained annulus pressure of gas wells in shale gas demonstration areas is improved effectively. This research achievement can be used as a reference for integrity management of cement sheath in the similar blocks.


*Keywords:* Sichuan Basin; Shale gas; Sustained annulus pressure; Hydraulic fracturing; Cement sheath integrity; Micro-annulus; Plastic deformation; Interfacial bonding strength; Young's modulus

## 0. Introduction

The “multi-stage fracturing + horizontal well fracturing” development mode is widely applied in the shale gas demonstration areas of the Sichuan Basin. In the course of fracturing, the wellhead pressure may be up to 90 MPa, which brings a challenge to the integrity of casing and cement sheath.

Scholars have conducted a series of studies on cement sheath integrity under wellbore pressure changes in terms of mechanical model, cement mechanical test and lab simulation experiment. Yin et al. [1,2] established an elastic analytic solution of casing-cement sheath-surrounding rock aggregation under non-uniform crustal stress. Li et al. [3], Sanit-Marc et al. [4] and Fan et al. [5] considered the factors like temperature stress and initial stress. Wan [6] used finite elements to build a model to analyze the mechanics of cement sheath under the conditions of eccentric casing and elliptic wellbore. All these models follow the elasticity theory to regard the casing, cement sheath and surrounding rock as elastomers. Triaxial test was conducted on cement in oil wells over recent years, showing that cement has an apparent plastic behavior

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**Nomenclature**

| | |
|---|---|
| $A$ | calculation parameter, which is used to judge the maximum and minimum principal stresses |
| $C$ | cohesion of cement sheath, MPa |
| $\varphi$ | internal friction angle of cement, rad |
| $d_n$ | micro-annulus, μm |
| $f_1, f_2, f_3, f_4, f_5, f_6, f_7$ and $f_8$ | intermediate variables |
| $p_1$ | pressure at interface of casing and cement sheath (contact force at the first interface), MPa |
| $p_2$ | pressure at interface of cement sheath and surrounding rock (contact force at the second interface), MPa |
| $p_i$ | pressure in casing, MPa |
| $p_o$ | pressure at external boundary of surrounding rock near the wellbore, MPa |
| $p_p$ | contact force at elastic−plastic boundary of cement sheath, MPa |
| $p_{1n}$ | pressure at first interface after unloading, MPa |
| $p_{2n}$ | pressure at second interface after unloading, MPa |
| $r$ | radius of a place of aggregation, mm |
| $r_1$ | inside radius of cement sheath, mm |
| $r_2$ | outside radius of cement sheath, mm |
| $r_i$ | inside radius of casing, mm |
| $r_o$ | outside radius of sidewall surrounding rock, mm |
| $r_p$ | radius of plastic zone in cement sheath, mm |
| $u$ | displacement of a place of aggregation, μm |
| $u_{so}$ | radial displacement of outer boundary of casing, μm |
| $u_{ci}$ | radial displacement of inner boundary of cement sheath, μm |
| $u_{co}$ | radial displacement of outer wall of cement sheath, μm |
| $u_{fi}$ | radial displacement of inner wall of surrounding rock, μm |
| $u_{ceo}$ | radial displacement of outer wall of elastic zone in cement sheath, μm |
| $u_{cpi}$ | radial displacement of inner wall of plastic zone in cement sheath, μm |
| $u_{cpo}$ | radial displacement of outer wall of plastic zone in cement sheath, μm |
| $u_{cin}$ | radial displacement of inner boundary of cement sheath after unloading, μm |
| $u_{son}$ | radial displacement of outer wall of casing after unloading, μm |
| $\sigma_r$ | radial stress, MPa |
| $\sigma_\theta$ | circumferential stress, MPa |

under high confining pressure [7,8]. Due to the complexity of plastic problem solution, finite element modeling is usually adopted in analysis [9−11], and only a few scholars conducted derivation of elastic−plastic mechanical model. Li et al. [12] adopted the Tresca criteria to discuss the elastic−plastic equation of casing−cement sheath−surrounding rock aggregation. Chen et al. [13] adopted the Mohr−Coulomb yield criteria to derive the elastic−plastic equation of casing-formation aggregation, and discovered through computation that, in the plastic formation, the casing load is larger than the elastic solution (up to 3%). Many institutions have conducted lab simulation experiment to simulate the effect of temperature and pressure variation on the integrity of cement sheath since the 1990s [14−16]. It is discovered that apart from the damage to cement sheath itself, the variation of temperature and pressure in the wellbore may result in micro-annulus at the cement sheath-casing interface (the first interface) or the cement sheath-surrounding rock interface (the second interface), and thus cause a failure of cement sheath integrity. Chu et al. [17] built an elastic−plastic mechanical model taking account of continuous variation of pressure in the wellbore to conduct computation on the whole process of pressure rise (loading) and drop (unloading) in the casing, so as to analyze the causes of micro-annulus, and they also derived equations for computing the size of micro-annulus.

An appropriate model should be built to analyze the fracturing process and clarify the cement sheath integrity failure modes, so that effective measures can be taken to ensure the integrity of cement sheath during hydraulic fracturing of shale gas reservoir. In this paper, the concept of modeling cement sheath integrity under the condition of variation of pressure in the wellbore in the processes like fracturing and production of shale gas reservoir is introduced. Then, based on the available formation data and operation data, the wellbore integrity issues occurred in the processes like reservoir stimulation of Well YS108H3-1 in the shale gas demonstration area in the Sichuan Basin, and corresponding solutions are put forward.

## 1. A mechanical model of cement sheath integrity under the condition of continuous casing pressure variation

The pressure in casing continuously changes in the processes of fracturing and production. During fracturing, for example, the wellhead pressure rises to a certain value and then unloads. In this paper, the phase of pressure rise is termed as loading phase and the phase of pressure drop is termed as unloading phase. The loading and unloading phases can be further divided based on the occurrence of yield or micro-annulus, for which the modeling methods are different. In this section, the continuous variation process of internal pressure is decomposed, and then, the modeling methods and thoughts of all the sub-processes decomposed are introduced respectively.

### 1.1. Decomposition of a continuous casing pressure variation process

The loading phase can be divided into elastic deformation phase and plastic deformation phase based on the yield status of cement. At the initial stage of loading, elastic deformation occurs in casing, surrounding rock and cement sheath. This