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The maximum permissible fracturing pressure in shale gas wells for wellbore cement sheath integrity

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ABSTRACT

Sustained Casing Pressure (SCP) has been recognized as a major problem in multi-fractured shale gas wells. The problem is attributed to the failure of cement sheath during the hydraulic fracturing process. Currently available mechanics models predict well integrity conditions with high error. We believe the reason is that the debonding at the casing-cement interface and plastic deformation of cement do not create significant axial channels for gas to migrate to the surface but the radial cracking of cement sheath is responsible for the gas migration resulting in the SCP. Although some mathematical models can predict radial cracking of cement sheath, they have limitations in applications because they do not account for the weakened cement sheath and reduced support from formation rock due to the low efficiency of cement placement in the annulus. An analytical model was derived in this work to predict the Maximum Permissible Fracturing Pressure (MPFP) due to radial cracking with consideration of the weakened cement sheath and the reduced support from formation rock. The results are in good agreement with observations in the Fuling shale gas field, China. Sensitivity analyses show that improving cement strength is not an effective means of increasing MPFP. The MPFP should be enhanced by increasing the thickness of the cement sheath using large wellbore size and improving the cement placement efficiency. This work also shows that cement sheath failure will occur before casing failure occurs in the hydraulic fracturing process. Therefore integrity of cement sheath should be considered in the hydraulic pressure design.

1. Introduction

Shale gas formations are essentially lithified clays with organic matter present in varying amounts. According to Katsube (2000) gas flows in shales through a network of pores with different diameters ranging from nanometers ($\text{nm} = 10^{-9}\,\text{m}$) to micrometers ($\mu\text{m} = 10^{-6}\,\text{m}$). The fine-grained rocks in the shale are micro-porous with permeabilities ranging from 10^{-6} to 10^{-3} md (Loucks et al., 2009; Wang and Reed, 2009). Due to the ultra-low permeability nature of shales, hydraulic fracturing (HF) is needed to improve well productivity (King, 2010; Meyer and Bazan, 2011; Chen et al., 2015; Zhou et al., 2016). The HF process makes the cement sheath behind well casing vulnerable to fail (Wang and Taleghani, 2014; Shadravan et al., 2015), resulting in gas leak along the cement sheath in the well annulus, leading to the occurrence of a phenomenon commonly called Sustained Casing Pressure (SCP). Landry et al. (2015) observed SCP as the presence of pressure in the annulus of nonstructural strings after fracturing treatment in the Cana Woodford shale. The SCP imposes danger to personnel, equipment, and environment.

A number of investigators have studied the issue of cement sheath integrity failure since 1990's (Goodwin and Crook, 1990; Jackson and Murphey, 1993a,b; Ugwu, 2008; Teodoriu et al., 2010; Li et al., 2017). Goodwin and Crook (1992) investigated the changes in cement permeability when different inner casing pressures were applied. There was a major increase in cement permeability after a 4000 psi cycle and a catastrophic increase after a 6000 psi cycle. Different cement failure types were observed in cement with different tensile strength. Cracks were initiated from interior of cement to the outer casing surface in tested cement with high tensile strength while cracks were initiated from inner surface to outer surface of casing in tested cement with low tensile strength. Jackson and Murphey (1993a,b) measured the cement permeability to gas and got similar results to Goodwin and Crook' experiments (1992). Recent research has indicated three main mechanisms that could cause the failure of cement sheath integrity. They are debonding, radial cracking, and plastic deformation (Ugwu, 2008; Shenold and Teodoriu, 2016). Debonding is due to loading and thermal

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stress between the cement and casing or between the cement and the rock formations (Ladva et al., 2005). Radial cracking and plastic deformation are often induced by a high net casing pressure during the HF process (Lecampion and Prioul, 2013).

Thiercelin et al. (1998) presented an analytical approach to the estimation of the stress in the cement. It was concluded that the cement integrity was influenced by the mechanical properties of cement and formation rock as well as the geometry of the cased wellbore. Bosma et al. (1999) raised a mathematic model to estimate the well sealant behavior. Mechanical properties of the sealant such as compressive strength, shear strength, bonding strength, and Poisson' ratio are needed to choose the suitable sealant. Bois et al. (2011) presented the cause of microannuli in the cement based on both mathematical analysis and experimental results. Microannuli were initiated due to the variations in formation stress, mud pressure, cement pore pressure, well bore temperature and so on. Li et al. (2015) investigated the effect of cement/formation stiffness on well integrity using an analytical solution. Shi et al. (2015) developed an analytical model to estimate the stress state of casing-cement sheath-formation system by considering the initial loaded state and wellbore temperature variation. Wang and Taleghani (2014, 2017) simulated the possible fracture propagation situations during hydraulic fracturing stimulation by running a coupled poroelastic model. Xi et al. (2017) used a new numerical model to analyze the effect of dynamic temperature on cement sheath integrity during multistage hydraulic fracturing process in shale gas wells.

The above-reviewed analytical and numerical models may adequately simulate the effects of wellbore pressure on the stress in the cement sheath under various operating conditions. However, results from these models are often inconsistent to field SCP observations. This is partially because cement sheath failure is not an adequate condition for an SCP to occur. Even if the cement failure is predicted accurately, other conditions are necessarily to cause an SCP. These conditions include the presence of a flow source and a continuous channel behind pipe up to surface. However, we believe that the currently used cement integrity models do have deficiencies in cement sheath failure prediction. For example, the debonding at the casing-cement interface and plastic deformation of cement do not create significant axial channels for gas to migrate to the surface but the radial cracking of cement sheath is more likely responsible for the gas migration resulting in an SCP. Although mathematical models for predicting radial cracking of cement sheath are available, they have limitations in application because they do not account for the weakened cement sheath and reduced support from formation rock due to the low efficiency of cement placement in the annulus. A new analytical model was developed in this study for predicting the radial cracking of cement sheath, considering weakened cement sheath and different degrees of support from the formation rock. Field case studies presented in this paper show that the new model gives results that are very consistent (92%) with field observations of SCP.

2. New mathematical model

Unlike those mechanical models mentioned in the previous section that define cement sheath failure either as radial debonding of the casing-cement interface or shear failure of cement, we define cement sheath failure as the formation of radial crack due to tensile failure of cement. This is because the tensile strength of cement (300 psi ~ 700 psi) is much lower than its compressive strength and the axial extension of the radial crack is more likely to reach the top of cement column than the debonding and shear-failure cracks that form with angles from the axial direction in the annular space. More importantly, most of the existing cement sheath integrity models do not take the worst case scenarios into consideration, such as the gap between formation rock and the cement. The gap reduces the thickness of the cement sheath. Moreover, it reduces the resistance of cement sheath against the inner casing pressure since the support of the formation to the cement sheath is significantly reduced.

In light of what proceed, accurate prediction of failure of cement sheath with a fluid gap is plainly quite a challenge to achieve. The term Maximum Permissible Fracturing Pressure (MPFP) is used to denote the down-hole pressure inside the casing that will cause radial cracking of the cement sheath. It is expected that the MPFP is determined by the tensile strength of set-cement and the degree of support from the formation rock for no-gap conditions or pore fluid for gap conditions behind the sheath. When the cement fully occupies the annulus, the cement will be supported by formation stress. Although the in-situ formation stress may be lower than formation stress near the wellbore, a conservative value for the MPFP can be estimated based on the in-situ stress. According to Timoshenko and Goodier (1961), Lame's solution can be used to calculate the tangential and radial stress at the inner surface of the cement sheath. Through the classical solution of Timoshenko, a relation between the pressure inside the casing and the tangential stress at the inner surface of the cement sheath is determined. The MPFP corresponds to the pressure inside the casing that is just high enough to cause a radial crack in the cement due to the tensile stress in the tangential direction exceeding the tensile strength of the cement. Details of the derivation of the MPFP are shown in Appendix A. The resultant form of the MPFP is:

$$MPFP = \frac{[(r_{so}^2 + r_{si}^2) - \nu(r_{so}^2 - r_{si}^2)][\sigma_T(r_w^2 - r_{so}^2) + 2\sigma_h r_w^2]}{2r_{si}^2(r_{so}^2 + r_w^2)} \tag{1}$$

where r_{so} = outer radius of casing.r_{si} = inner radius of casingr_w = wellbore radiusν = Poisson's ratio of set cementσ_T = tensile strength of set cementσ_h = In-situ stress of the formation rock.

When the annulus is not fully occupied by the cement, the cement will be supported with formation pore pressure around the wellbore. Through the formation pore pressure may change during fracturing process, a conservative value for the MPFP can be calculated using the initial formation pore pressure. The thickness of cement sheath that is associated with the cement placement efficiency affects the burst resistance of the cement sheath. Similar to Eq. (1), the following Eq. (2) is derived and derivation is shown in Appendix A.

$$MPFP = \frac{[(r_{so}^2 + r_{si}^2) - \nu(r_{so}^2 - r_{si}^2)][\sigma_T(r_{co}^2 - r_{so}^2) + 2p_p r_{co}^2]}{2r_{si}^2(r_{so}^2 + r_{co}^2)} \tag{2}$$

where r_{co} = outer radius of the cement sheath.

p_p = formation pore pressure.

The value of r_{co}can be estimated according to the cement placement efficiency. Since 1960's, Cement Bonding Logs (CBL) and Modern Ultrasonic Cement Logs (UCL) have been utilized to estiamte the cement placement efficiency (Pardue et al., 1963; Bade, 1963; Sheives et al., 1986). The volume fraction of cement in the annular space can be used to estimate the outer radius of cement through Eq. (3)

$$E_c = 1 - \frac{\pi r_w^2 - \pi r_{co}^2}{\pi r_w^2} \tag{3}$$

which gives

$$r_{co} = r_w\sqrt{E_c} \tag{4}$$

where E_c is the cement placement efficiency. As a rule of thumb, in order to prevent SCP, the safe value of the cement placement efficiency factor should be larger than 0.8 for at least 50 feet of cement sheath for wellbores in water flooding projects (Sheives et al., 1986). This criterion may not be safe for wellbores in multi-stage hydraulic fracturing because repeated high pressure loads can cause growth of axial cracks in the cement sheath against the cap rock.