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Analysis on integrity of cement sheath in the vertical section of wells during hydraulic fracturing

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ABSTRACT

The sustained casing pressure (SCP) problems occur mainly in intermediate casing that might affect the safety and efficiency of shale gas production. Cement sheath is the main barrier against leakage and migration of gas from the pay zone to the shallow zones. Since the production casing is cemented all the way up to the intermediate casing in the vertical section of the well, the in-situ stress can only act on the intermediate casing and not directly on production casing. Based on this situation, an analytical model considering the well completion steps is established to study the integrity of cement sheath as a two-layer casing-cement system. The effect of mechanical and geometrical parameters of casing and cement are further investigated through a sensitivity analysis. The results show that the tensile failure more likely occurs at the inner face of the cement sheath in the intermediate casing. The casing thickness is in favor of decreasing the tensile stress in the cement sheath. But on the contrary, increasing the thickness and elastic modulus of the cement sheath may increase the risk of tensile failure in the cement sheath while reducing the costs. However, an appropriate increase of back pressure in the annulus during cementing is beneficial to reduce the tensile stress in the cement sheath.

1. Introduction

The application of hydraulic fracturing and horizontal drilling has made the economic exploitation of natural gas from low-permeability shale formations possible. These technology advances have unlocked vast new energy sources and initiated significant changes to the gas industry around the world. After the United States has achieved commercial production of shale gas, the investment in producing shale gas is widely growing around the world. More and more shale gas fields are explored and thousands of shale gas wells are drilled in America, Canada and China (Boyer et al., 2011; Vidic et al., 2013). But the sustained casing pressure (SCP) problems (the casing pressure buildup in the annulus) exist in a large number of shale gas wells threaten the efficient and safe exploitation of shale gas in some places (Panjwani et al., 2017).

Cementing is mainly to support the casing and isolate the wellbore from hydraulic communication with other formations. In the studies about the integrity of cement sheath, the cement is treated as elastic-brittle or poroelastic material and the stress in cement sheath is affected by the cement properties (Ghabezloo, 2010; Taleghani et al., 2017). Loads on the cemented casing system are fluid pressure in production casing and in-situ stresses on the exterior side. EI-Sayed and khalaf, 1992, Fang et al., 1999 and Jo and Gray, 2010 have established linear models to estimate stress components in casing and cement under non-uniform in-situ stress. The periodic change of fluid pressure and temperature in casing may also cause the failure of the cement sheath and generate micro-annulus at casing-cement or cement-rock interface (Dusseault et al., 2000; Richard et al., 2014; Chu et al., 2015; Taleghani and klimemko, 2015; Wang and Taleghani, 2017). The fatigue failure of the cement sheath is also studied (Nikolaus and charles, 2007; Yuan et al., 2013; Feng and Gray, 2017).

In shale gas wells, the high fluid pressure and its large fluctuations during fracturing treatments may lead to the generation of SCP. During hydraulic fracturing in shale gas wells, incomplete cementing and weak cement sheath can cause shear failure and evolution of long fractures broaching along the vertical section of the well (Kim et al., 2011, 2016; Wang and Taleghani, 2014; Taleghani and Wang, 2017). The shear failure of the cement sheath and casing deformation during hydraulic fracturing is also studied by Liu et al. (2016) and Pereira et al. (2017), the shear failure of cement sheath can be reduced by decreasing the elastic modulus.

In the vertical section of the well, the structure of the well from

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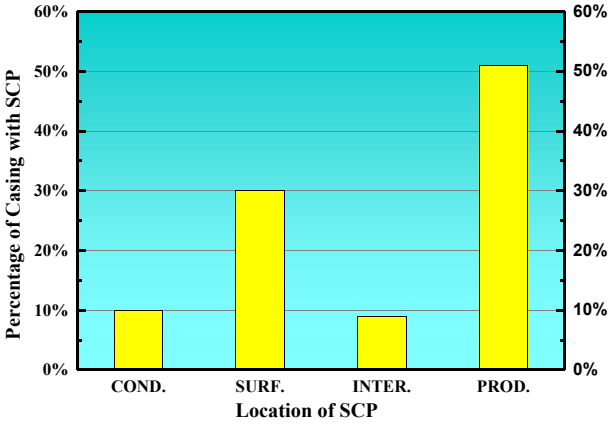

Fig. 1. Location of the SCP in wells of Gulf of Mexico.

inside out is consisted of the production casing, cement sheath, intermediate casing, cement sheath and then the formation rock. Due to the presence of two layers of casing and cement sheath (see Fig. 4) and the high fluid pressure in the casing during the hydraulic fracturing treatment, the integrity of the cement sheath differs from the problems studied in the above-mentioned references that the steps of well completion is not considered in the previous study (Goodwin and Crook, 1992; Wang and Taleghani, 2014). It is notable that this problem usually happens in areas where tubing is not used for pumping fluid during hydraulic fracturing. In this paper, a model to determine stress components in the cement sheath, in the described situation, is established by considering the well completion steps.

2. Overview of SCP in oil and gas wells

It is frequently observed in some areas to have gas migration to the surface through the well annulus. About 43% of 15,000 tested wells, inspected in Gulf of Mexico, have shown some degrees of cement damage after well completion that was a triggering point for formation of sustained casing pressure (Muehlenbachs, 2011; Vengosh et al., 2014). Different locations for presence of SCP in GOM are shown in Fig. 1 (Bourgoyne et al., 2000) where SCP mostly exists outside the production casing.

Based on the feedback from operators in the Marcellus shale, 25% of the wells located in this area still show measurable annular surface gas (Williams et al. , 2011) as shown in Fig. 2. In the Fuling shale gas field in China, the percentage of wells with SCP reaches to 86% and the percentage of SCP in the intermediate casing extends to 71% (Fig. 2), which means that gas migration in the cement sheath between the production casing and intermediate casing is a serious problem in this field.

The failure of the cement sheath in a well has been determined with various criteria. Mohr-Coulomb criterion is used very frequently to determine the shear failure of the cement and tensile criterion is used for the tensile failure (Fourmaintraux et al., 2005). Different types of cement failure are shown in Fig. 3 (Saint-Marc et al., 2008; Bois et al., 2012; Wang and Taleghani, 2012; Shadravan et al. , 2015). These different types of cement failure can be simply classified as debonding at the inner interface of the cement sheath (Fig. 3a), debonding at the outer interface of the cement sheath (Fig. 3b), shear failure of the cement sheath if it is exposed to a large deviatoric stress (Fig. 3c), or radial cracks if the inner-pressure of cement sheath is much larger than the outer-pressure (Fig. 3d).

During hydraulic fracturing, the fluid pressure inside the casing would increase the radial stress in the cement sheath hence no debonding is expected to occur unless due to residual plastic deformations when the fluid pressure drops or due to shear stresses developed near the interfaces.

3. Analytical model of stress in cement

A sketch of the vertical section of a cemented well is shown in Fig. 4. The mechanical model can be simplified as a two layered casing-cement system (we call it casing-cement system later). The intermediate casing is cemented to the formation and the production casing is cemented to the intermediate casing. Drilling and completion of shale gas wells in Fuling include the following three steps. First, the vertical section of the well is drilled and then the intermediate casing is cemented to the formation. In the next step, the horizontal section of the well is drilled and the production casing is cemented to the formation in the horizontal section up to the intermediate casing at the vertical section. Finally, the hydraulic fracturing treatment will be executed at the horizontal section of the wellbore.

The wellbore is assumed to be long enough that the problem can be assumed as a plane strain problem. In the vertical section, we have minimum horizontal stress σ_h and maximum horizontal stress σ_H. During a hydraulic fracturing treatment, the fluid pressure in the production casing will increase significantly and the temperature around the well would decrease due to pumping a large volume of cold fluid through the production casing which induces thermal stress in the system.

To have a clear notation about different interfaces involved in this problem, casing strings, cement sheath and formation from the production casing to formation are numbered as ring 1 to ring 5, respectively. The interfaces between these rings are also numbered from I to IV accordingly.

In previous studies about the integrity of the cement sheath in oil and gas wells, all loads are assumed to act on the casing-cement system simultaneously and the sequential steps of cementing works is ignored in stress analyses. Model A described in Fig. 4 is a representative of such models. First, there is no load on the system (Fig. 4 (A1)), then the in-situ stress loads act on model boundary (ring 5) and the fluid pressure

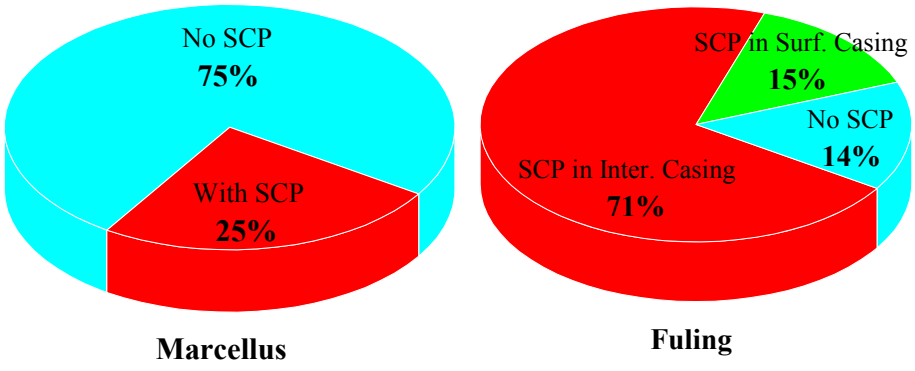

Fig. 2. Summary of SCP in Marcellus shale gas field and Fuling shale gas fields.