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Cement sheath integrity analysis of underground gas storage well based on elastoplastic theory

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ABSTRACT

For injection & production well built in underground gas storage (UGS), sealing failure of cement sheath is one of the major factors threatening wellbore integrity due to continuous varied casing pressure and temperature. Cement sheath may deform plastically in the process of gas injection and lose airtightness if unloading casing pressure. In view of this, an analytical model of the stress, displacement and interaction of casing-cement sheath-surrounding rocks subjected to inner casing pressure and outer radial far-field in-situ stress and debonding of cementing surfaces were derived with due consideration of varied casing pressure, temperature and pore pressure due to cyclic injection and production. In this model, casing, cement sheath and surrounding rocks were seen as multi-layer cylinders and were analyzed based on thermoelastic, elastoplastic and poroelastic theory, respectively. A demonstration calculation is performed to reveal the stress and displacement of cement sheath under conditions of cyclic loading and unloading. The model was compared and validated by finite element simulations. Factors affecting the interaction of cement-casing and cement-rocks and the formation of micro-annulus were analyzed. As a result, when loading casing pressure, the radial contact stress on the bonding surfaces increases nonlinearly and cement sheath may deform plastically. In the process of unloading casing pressure, if low far-field in-situ stress exists, the radial contact stress tends to transform from compression to tension leading to the separation of bonding surfaces. The variation of temperature, pore pressure and far-field in-situ stress are key factors affecting the stress & deformation of cement sheath and micro-annulus. For cement with large elasticity modulus and small Poisson's ratio, plastic deformation and micro-annulus are prone to forming. Thus, the reasonability of the application of ultra-high toughness cement in UGS well has been verified. The results are of guiding significance to the operating optimization, micro-annulus prevention and wellbore integrity improvement of UGS wells.

1. Introduction

With the advances of natural gas industry, underground gas storage (UGS) plays an increasingly important role in energy storage and supply in order to contribute to the development of green, low-carbon economy. Maintaining wellbore integrity of injection & production well is a key issue in the operation of UGS concerning the safety of staff, surrounding environment and UGS itself. The sealing failure of cement sheath is one of the major risks threatening wellbore integrity (Glen, 2009). Sustained casing pressure (SCP) is a common phenomenon raising potential risk concerns. One of the major reasons accounting for SCP is gas leakage due to integrity failure of cement sheath (Milanovic and Smith, 2005; Zhang and Bachu, 2011). Watson and Bachu (2009) has conducted statistical analysis of the wellbore integrity issue locating at Alberta test area, Canada. The result shows that about 64% of the 20,725 wells has been detected gas flow at wellhead in the annuli outside casings and poor cementing quality is a major contributor to gas migration upward. Since the wellbore of UGS serves to both injection and production, the cement sheath is prone to sealing failure due to the impact of continuous variation of pressure and temperature, leading to SCP.

The cement sheath of UGS wellbore serves in complex working conditions due to cyclic injection and production of natural gas and the resulting changes of temperature and pressure along wellbore and pore pressure. With continuous injection of natural gas, the temperature in areas adjacent to wellbore decreases and the pore pressure increases gradually. On the contrary, when gas is produced, wellbore temperature rises and the pore pressure drops. The variations of casing pressure, wellbore temperature, pore pressure under different working conditions

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result in the variation of in-situ stress field (Liang et al., 2004). This coupling variation of temperature, pressure, in-situ stress field will bring about the alternate change of contact forces exerted by casing and surrounding rocks on cement sheath and the following types of failure: (1) fracture of cement sheath, as the inherent inner micro-cracks may extend and connect, cement sheath may fracture radially; (2) separation of bonding surfaces and formation of micro-annulus; (3) permanent plastic flow of cement sheath (Shadravan et al., 2014; Ugwu, 2008). Decline of sealing capacity due to contact stress decrease or interface debonding and radial crack are dominating mechanisms for sealing failure of cement sheath (Lecampion et al., 2011). Two main factors accounting for micro-annulus are plastic shrinkage deformation and shearing failure of cement sheath. The casing-cement sheath-surrounding rocks assembly of UGS well is subjected to continuous loading and unloading inner pressure under working conditions of cyclic gas injection and production. When loading casing pressure, cement sheath may deform plastically. Once the pressure unloads, the casing, cement sheath and rocks may not contract synchronously due to plastic deformation of cement sheath and mechanical properties difference. Forming micro-annulus or debonding of cementing surfaces may occur. Liu et al. (2014) analyzed the effect of change in pressure inside wellbore on the sealing integrity of cement sheath and pointed that fatigue of cement sheath subjected to periodic alternating load requires attention. Therefore, elastoplastic analysis of cement sheath under continuous variation of pressure and temperature is necessary in order to control plastic deformation and prevent micro-annulus.

Ladva et al. (2013) pointed that factors affecting debonding of cement sheath include work load, thermal stress, incomplete removal of mud cakes, roughness of formation surface and contraction due to cement dehydration, etc. Many scholars have conducted fruitful research on the interaction of casing-cement-formation assembly and integrity failure of cement sheath. The methods employed can be categorized as analytical models, physical models and finite element models.

(1) Deriving analytical models based on elastic or elastoplastic mechanics and plane strain assumption is a widely-used method to characterize the stress and failure of cement sheath. Thiercelin et al (1998a & 1998b). established a prediction model of mechanical integrity failure of cement sheath and analyzed some key controlling factors based on linear elasticity theory, assuming that formation, cement and casing all are isotropic and homogenous linear elastic materials. Li et al. (2005), Yin et al. (2006) and Chen and Cai (2009) focused on the plastic deformation of cement sheath and obtained analytical solutions to the deformation and stress of casing-cement-surrounding rocks assembly according to basic elastic-plastic principle. Bois et al. (2011) modeled the formation of micro-annulus analytically by analyzing the volume variation and heat produced in the process of dehydration and thermo-poro-elasto-plastic features of cement during and after dehydration. In addition, Teodoriu et al. (2010), Haider et al. (2012) and Yin and Gao (2015) also built analytical models describing the interaction of cement-casing and cement-surrounding rocks applying elasticity theory and different failure criteria, considering the effect of pressure and temperature variation during the operation of wellbore.

(2) Experimental research has been conducted to verify and improve the theoretical model. Boukhelifa et al. (2004) built large-scale experimental facilities and conducted laboratory tests of the cement sheath with confining pressure to simulate the behavior of sealing property, failure modes and related factors under various downhole stress conditions. Tang et al. (2012) also performed physical experiments to simulated the stress and failure of casing-cement sheath-formation assembly subjected to high inner pressure and measured the strain value and fracture load of cement sheath under the action of biaxial stress.

(3) Finite element analysis (FEA) has been applied as an effective tool for the stress and integrity failure analysis of cement sheath under various conditions. Wang and Taleghani (2014) built a 3D numerical model predicting the spatial distribution of stress and spatial failure pattern of cement sheath by cohesive crack method, considering the spatial non-uniform failure characteristics of cement sheath around wellbore in different orientations. Andrade and Sangesland (2016) conducted finite element analysis of formation-cement-casing assembly, compared the sensitivity of related factors such as material properties, geometry, characteristic load, especially thermal stress, and revealed the failure mechanism of cement sheath.

In-situ stress, variation of wellbore temperature and pressure affect the stress and integrity of cement sheath significantly. Temperature-solid coupling and fluid-solid coupling analysis is required in modeling the interaction of casing-cement sheath-surrounding rocks. Also, the effect of non-uniform in-situ stress field and temperature field on the stress and failure mode of cement sheath has raised concern. Li et al. (2009) analyzed the radial distribution of thermal stress and thermal displacement of casing-cement sheath-formation system. As a conclusion, both the radial thermal displacement and thermal stress first increases and then decreases radially and the peak values locate on the interface of cement-rocks and the outer wall of casing. Li et al (2010 & 2012). analyzed the stress and displacement of cement sheath in non-uniform in-situ stress field coupling the variation of temperature and pressure. He concluded that non-uniform distribution of stress exists around wellbore and cement sheath may fail in shear in non-uniform in-situ stress field. Zhang et al. (2015) proposed an analytical model describing integrity failure of cement sheath under condition of solid-temperature coupling in the light of solid-temperature coupling controlling equations and elasticity mechanics using Mises, Drucker-Prager and JRC-JCS failure criteria. The non-uniform in-situ stress field and temperature field were considered. Xu et al. (2015) and Zhang et al. (2016) studied the influence of wellhead casing pressure (WHCP) on the integrity failure of cement sheath based on elasticity and concluded that the hoop tensile stress produced by WHCP is a major contributor to integrity failure. The safety coefficient of cement sheath decreases with the increase of WHCP.

All the above research on cement sheath does not involve the case of plastic deformation and formation of micro-annulus under continuous varied casing pressure and temperature and neglects the poroelastic properties of surrounding rocks. Actually, casing pressure, temperature and pore pressure vary continuously during the operation of UGS and cement sheath is loaded and unloaded continuously, which is likely to cause plastic deformation in the process of loading and to form micro-annulus when unloading. Hence in view of the service conditions of UGS cement sheath, appropriate elastoplastic analysis needs to be conducted with due consideration of varied casing pressure and temperature, pore pressure and far-field in-situ stress. Currently, seldom elastoplastic analytical model of stress, displacement of cement sheath and formation of micro-annulus under continuous loading and unloading has been built.

This paper is organized as follows. First, casing, cement sheath and surrounding rocks of UGS well are characterized through thermoelastic mechanics, elastoplastic theory and poroelastic theory, respectively. An analytical model of the interaction of casing-cement-surrounding rocks and formation of micro-annulus in the process of continuous loading and unloading is derived. Second, a demonstration calculation is performed to reveal the stress and deformation features of cement sheath when loading and unloading casing pressure. Also, the model is compared and validated with the result of FEA. Third, affecting factors on contact stress such as temperature, pore pressure, radial in-situ stress, mechanical parameters of cement stone are analyzed. At last, conclusions are drawn. The results are expected to guide UGS operation optimization, micro-annulus prevention and wellbore integrity maintenance.