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Research on the law of mechanical damage-induced deformation of cement sheaths of a gas storage well

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A B S T R A C T

Although the technique of micro-sphere low-density cement slurry has been effectively applied in solving cementing problems of gas storage wells, little research has been conducted on the mechanical damage and failure of micro-sphere low-density cement sheaths subjected to alternating load in the well. In this paper, a simulative wellbore was used to obtain the experimental phenomena of cement sheaths under periodic loading. Based on such phenomena, the law of mechanical damage-induced deformation of micro-sphere low-density cement sheaths was studied via triaxial cyclic loading, the classic theory of fatigue damage mechanics, low-field nuclear magnetic resonance, the permeability and porosity test and the SEM test. The experimental results indicate that temperature has the greatest impact on the mechanical integrity of micro-sphere low-density cement sheaths and that the damage-induced deformation quantity of the cement sheath at a curing temperature of 90 °C is greater than that at a curing temperature of 60 °C. At a curing temperature of 60 °C, the cement sheath suffered fatigue damage after certain periods of cyclic loading, and the irreversible deformation suddenly increased. For a curing temperature of 90 °C, the cement sheath was less likely to be subjected to elastic deformation because of the many harmful pores within and thus corrupted quickly after loading. The following three damage failure modes of micro-sphere low-density cement sheaths occurred after triaxial cyclic loading and unloading micro-sphere ruptures, cracks between pores, and connected cracks among cement matrices. Therefore, the selection of micro-spheres and the mechanical modification of cement sheaths are key contributors to the integrity of micro-sphere low-density cement sheaths.

1. Introduction

As a widely applied clean energy, natural gas features reduced environmental pollution, mass consumption, abundant quantities as well as other advantages. However, when storing natural gas, it is often necessary to re-inject the extracted resource from a gas field (gas reservoir) into underground gas storage under sealed conditions. Due to the complicated geological conditions in China, low-pressure and leakage-prone formations are often found during drilling in many gas storage wells (Raza et al., 2016; Sepp et al., 2009). Therefore, the micro-sphere low-density cement slurry technique is often employed in primary cementing operations to mitigate the risks of leakage. With hollow micro-spheres as light-weight additives, the density of micro-sphere low-density cement slurry can be adjusted from 1.2 to 1.6 cm^3; therefore, the micro-sphere low-density cement slurry is effectively applied to cementing of long-cemented, low-pressure and leakage-prone wells (Sugama and Wetzel, 1994; Murali and Tanner, 1987; Ripley et al., 1981).

Well cementing is a process in which casing pipes are set at a certain drilling depth into the stratum, and then cement slurry is used to fill the annular space outside the casing pipes. After coagulation and hardening within the scheduled time, cement slurry can support the casing pipes and realize zonal isolation in the stratum (Lyons et al., 2016). As shown in Fig. 1, when the gas storage well is in operation, the cement sheath experiences an internal pressure increase in the case of gas injection (Fig. 1b) and an internal pressure decrease in the case of gas production (Fig. 1c). Therefore, the micro-sphere low-density cement sheath in the wellbore has to bear alternating load caused by gas injection and production for a long time. When the cement sheath suffers the maximum load change, the integrity of the combination of casing

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pipe – cement sheath – well wall rock is compromised, thus destroying the integrity of the cement sheath and further leading to inevitable deterioration or even loss in the isolation of the sheath against the oil, gas and water layers. Consequently, fluid channeling occurs among the layers, and the sheath is corroded. Finally, the oil/gas well stops working. At present, scholars at home and abroad mainly focus on the engineering performance of the low-density cement slurry system but seldom study the mechanical performance of a long-cemented cement sheath under cyclic loading in the well (Shadravan et al., 2014; Wilcox and Oyeneyin, 2016; Bois et al., 2012).

In 1992, Goodwin and Crook (Goodwin et al., 1992) made a simulative wellbore using 139.7 mm inner pipe and 193.7 mm outer pipe. After the cement coagulated, they added pressure and hot oil to the inner pipe to simulate a real wellbore to test how the changes in the temperature and internal pipe pressure impact the integrity of the cement sheath. Through this experiment, Goodwin and Crook demonstrated how changes in the temperature and internal pressure of the casing pipe caused stress that destroyed the structure of the cement sheath, but they did not take into account the impact of confining pressure from the stratum on the cement sheath. In 2013, Yuan (Zant et al., 2007; Yuan et al., 2013) from Texas A&M University designed a simulative experiment, in which he put a casing pipe into a resin outer casing and injected cement into the annular space. In the experiment, axial pressure was directly applied to the casing pipe to cause radial deformation on the cement sheath. In this way, Yuan aimed to study the impact of low stress fatigue loading on the isolation performance of the cement sheath. Nevertheless, he did not consider the impact of confining pressure from the stratum and temperature on the cement sheath. In 2016, Li et al. from Southwest Petroleum University designed a set of simulative wellbore devices by adopting the theories of geometric similarity and stress equivalence. They exerted a loading process on this designed device equivalent to that of a cement sheath in a real wellbore under changing conditions, aiming to study the failure mode and mechanism of cement sheaths through gas logging and CT scanning. Unfortunately, the impact of cyclic loading on the mechanical properties of the cement sheath was beyond the scope of their study (Li et al., 2016).

The above-mentioned studies concerning the mechanical properties of cement sheaths for zonal isolation fail to take account the impact of cyclic loading on the mechanical properties of the cement sheath; and some of them do not consider the impact of temperature and confining pressure. To our knowledge, a long-cementing sheath in actual working conditions must bear continuously changing external load, for example, the internal pressure of the wellbore. In addition, for cement sheaths in some long-cemented well sections with large temperature differences, their mechanical properties may also be damaged by the temperature change. In this context, a real wellbore was simulated to analyze the mechanical deformation characteristics of low-density cement sheaths through triaxial cyclic loading. The present study looks into the mechanical damage-caused by the deformation law of low-density cement sheaths subjected to cyclic loading under different curing temperature conditions by combining the classic theory of fatigue damage mechanics, low-field nuclear magnetic resonance imaging technology, information about the porosity, and the permeability and microstructure of the cement sheath. Therewith, a theoretical principle and scientific basis can be developed for the modified design of the low-density cement slurry system and for the improvement of the performance of long-cementing sheaths in a wellbore (Bui and Tutuncu, 2013).

2. Description of the experiment

2.1. Experimental materials and workflow

Conventional-density cement slurry and low-density cement slurry were prepared for the experiment according to the formula used for gas storage wells in China. The temperature at the section cemented with micro-sphere low-density cement slurry ranges from 60 °C to 90 °C. Main experimental materials are G-grade oil well cement (Aksu Qingsong Cement Plant), 3 M hollow microspheres (compressive strength > 80 MPa), micro-silicon (Tuoyang Brand, Leshan City), fluid loss additives and dispersion agents (field sampling). The formula for conventional-density cement slurry consisted of 100% G-grade cement +30% micro-silicon +10% silica fume +4.5% fluid loss additive +1.5% retarder +0.5% dispersion agent, 1.88 g/cm^3 in density, 0.44 in water-cement ratio. The formula for the low-density cement slurry consisted of 100% G-grade cement +25% 3 M hollow micro-spheres +25% micro-silicon +6% fluid loss additive +3% dispersion agent, 0.44 in water-cement ratio, 1.38 g/cm^3 in density.

The workflow of the research is presented below (see Fig. 2):

2.2. Experimental method and process

2.2.1. Test with a simulative wellbore device

In consideration of the structure and size of a real wellbore, stratum temperature and pressure, and internal pressure in the

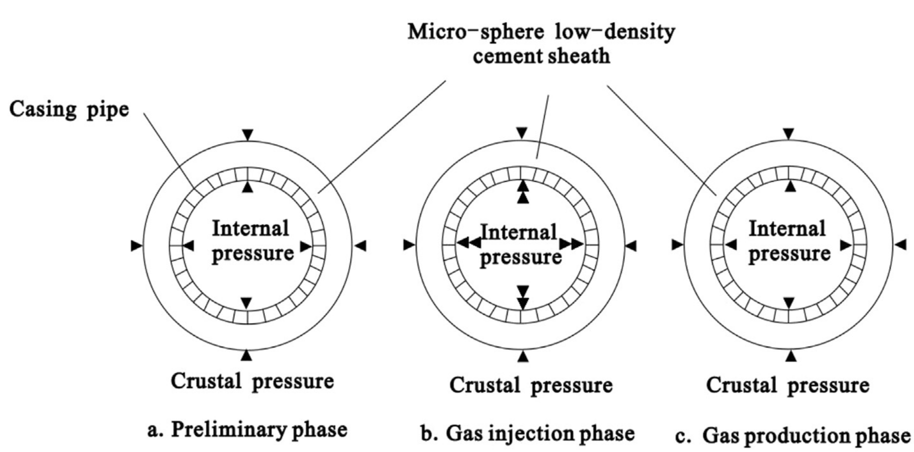

Fig. 1. Internal pressure change process of cement sheath for cementing.