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Study of the failure mechanisms of a cement sheath based on an equivalent physical experiment

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ABSTRACT

Cement sheaths are a key part of borehole integrity in oil and gas wells and have a direct influence on the life cycle of oil and gas wells. The reasons for the bearing failure of cement sheaths under complicated well conditions are of concern. According to the principle of geometric similarity and stress equivalence, a well bore simulator was designed to simulate the actual casing program, down-hole temperature and pressure environments, continuous changes in the internal casing pressure and to create an bearing process equivalent to that of the actual cement sheath under changing working conditions in order to explore cement sheath failure mechanisms. In the experiment, under fluctuating changes in the internal casing pressure and low confinement pressures, the cement sheath was cracked in the radial direction, but under high confinement pressures, the sheath became separated from the casing without macro cracks. A CT scan of the cement sheath under high confinement pressures indicated a reduction in its pore volume and total volume and the appearance of a micro-annulus on its cementation plane with the casing. Additional CT scans of the internal part of the cement sheath by drill sampling through the interface, however, exhibited an obvious difference in the particle distribution between the interface and the interior. High-strength particles moved from the interface to the interior, whereas low-strength particles were crushed at the interface, and the intensity decreased at the interface and increased in the interior. Based on the results of this experiment, it can be concluded that there were two primary reasons for the bearing failure of the cement sheath: 1) tensile fractures under low confinement pressures and 2) the separation of the interface under high confinement pressures, the microscopic mechanism of which was that the pore volume was reduced and that the skeleton particles of the interface were crushed or migrated under load. The study provides significant guidance that will be useful for guaranteeing cement sheath integrity in the future.

1. Introduction

Cement sheaths, which are formed through the solidification of the cement paste after the cementing operation to provide interlayer isolation for the stratum and protection and support for the casing, is a crucial follow-up for well drilling and oil gas exploitation (Li et al., 2008; Zhou et al., 2013). However, the vulnerability of the cement sheath under complex forces from follow-up operations, for example, perforation, fracture and exploitation, as well as the confinement pressures of the underground formation, may cause failures in the interlayer isolation of the oil gas well and is adverse to oil gas exploitation and stimulation (Yang et al., 2012; Guo et al., 2013; Shadravan et al., 2014). To date, many studies on the integrity of the cement sheath using theoretical models have been conducted by domestic and international scholars, but there have been few studies of bearing failure mechanisms using well bore simulation experiments (Bois et al., 2012; Bui & Tutuncu, 2013; Wang & Taleghani, 2014; Xu et al., 2015).

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Goodwin and Crook built a simulation well bore with a 139.7 mm inner pipe and a 193.7 mm outer pipe. After the cement solidified, they pressurized and injected hot oil into the inner pipe to simulate the influence of the well bore operation, test temperatures and changes in the internal pipe pressure on the integrity of the cement sheath. This experiment demonstrated damage caused by induced stress (generated during changes in the temperature and internal pipe pressure) to the structure of the cement sheath, but it failed to take into consideration the influence of the confinement pressure from the formation (Goodwin & Crook, 1992). Yuan, from Texas A&M University, developed a design for a simulation experiment that placed a casing inside an outer resin cylinder and then poured cement into the annular space to study the influence of a low-stress fatigue load on the isolation performance of the cement sheath. This experiment applied direct axial pressure to the casing, which induced radial deformation on the cement sheath, but the experiment did not consider the influence of confinement pressure and temperature (Nikolaus et al., 2007; Pang et al., 2012; Yuan et al., 2013). Andrade, from the Norwegian University of Science and Technology, placed a casing in the center of a man-made rock, injected cement into the annular space, heated and cooled the casing interior after the cement solidification to generate induced stresses on the cement sheath and observed a breakthrough flow channel in the cement sheath. Nevertheless, they also failed to consider the influence of the confinement pressure (Albawi et al., 2014; De Andrade et al., 2014, 2015).

None of the above-mentioned simulation experiments considered the tremendous influence of the confinement pressure, under which the set cement may turn from a hard brittle material into a partially extensible brittle plastic material (Ladva et al., 2005; Li et al., 2007). Therefore, this paper reports the design of a well bore simulator and set of equivalent physical experiments based on the principle of geometric similarity and stress equivalence, which were used to create a bearing process equivalent to that of an actual cement sheath under changing working conditions in order to study using gas surveys and CT scans the causal modes that produce the failure of cement sheaths.

2. Equivalent physical experiment for a cement sheath

2.1. Experimental facility

A load equal to that borne by the cement sheath under actual working conditions (e.g., including effects caused by the dimensions of the casing program, formation temperature and pressure and internal casing pressure) can be applied to the well bore simulator through stress equivalence, and an equivalent stress value can be obtained by adjusting the internal pressure, thereby creating an bearing process that is equivalent to that of the actual cement sheath under changing working conditions. The transmission of the stratum pressure was simulated by applying pressure to water or oil with a confinement pressure pump (7) to act on a rubber sleeve (2). The stratum temperature was simulated with a heating jacket (5) on the kettle body wall (1). The changing pressure in the actual well bore was simulated by adjusting the internal casing pressure with the internal pressure pump (9). See Fig. 1 for the design principle of the simulator and Fig. 2 for the real object.

2.2. Experimental subject and material

During a survey, it was found that an oil field well X suffered from severe sustained casing pressure (in the annular space C) after sustained operation, despite the high cement job quality of its technical casing (250.83 mm), as demonstrated by well logging. This, according to analysis, was mainly caused by the bearing failure of the cement sheath. Therefore, two points, one at a shallow layer and the other at a deep layer of the well, were adopted as the research objects. A simulation experiment was carried out for the two points with the same cement slurry formulation, i.e., Aksu Class G cement +60% fine iron ore +27% fine silicon +8% micro silicon +4% sodium chloride +4% filtrate reducer +2% dispersing agent +0.8% extender + water and the same experimental samples, i.e., a lime sample and water sample, including Aksu Class G cement (provided by Xinjiang Aksu Cement Plant), fine iron ore, fine silicon, micro silicon, filtrate reducer 906, dispersing agent 806 and extender 606 (all provided by Rand (Lang fang) Petrochemical Environmental Protection Equipment, Co. Ltd.), but under different conditions.

2.3. Experimental procedural

A cement slurry with a density of 2.2 g/cm^3, prepared per the API standard, was injected into a cement sheath curing device and then into an OWC-9390Y type pressurized curing kettle for curing. The formed cement sheath was removed and placed into the well bore simulator, the confinement pressures and temperatures were set equal to those in the shallow and deep layers in the formation in the actual situation, the cement sheath was ventilated, and the internal casing pressure was adjusted. Subsequently, the equivalent internal pressure of the simulator was calculated through stress equivalence based on the change values of the confinement pressures and temperatures at the two points in the shallow and deep layers of the stratum as well as the internal casing pressure under actual working conditions. During the experiment, a steady pressure was maintained for 10 min to observe gas migration, which, if any, would indicate damage to the structure of the cement sheath. See Table 1 for the experimental conditions and Tables 2 and 3 for the results.

3. Experimental results and discussion

3.1. Test results of well bore simulator

The data in Table 2 show that under low confinement pressures, no gas migration in the cement sheath was observed after the actual casing pressure was increased from 30 MPa to 50 MPa and remained steady for 10 min. However, when the internal pressure reached 60 MPa and was kept steady for 1 min, gas migration occurred, which indicated that the structure of the cement sheath was compromised. When the internal pressure was further increased to 70 MPa and then decreased to 30 MPa, gas migration was still occurring, which indicated that once the structure was compromised, the cement sheath completely lost its isolation ability.

The data in Table 3 show that under high confinement pressures, no gas migration of the cement sheath was observed after the actual casing pressure was increased from 60 MPa to 100 MPa and remained steady for 10 min, which indicated that the structure of the cement sheath remained uncompromised. However, when the pressure was decreased to 90 MPa and remained constant for 2 min, gas migration occurred, which indicated that the structure of the cement sheath was compromised. Because the that the deformability of the casing was far greater than that of the cement sheath, when internal casing pressure increased to 100 MPa, it was subjected to plastic deformation, whereas the casing suffered elastic deformation; when internal casing pressure decreased to 90 MPa, the casing recovered, but the cement sheath remained deformed, which led to separation and the development of the micro-annulus and finally the gas migration occurred.

After the experiment, it was found that the cementation of the