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Cement Sheath Failure Mechanisms: Numerical Estimates to Design for Long-Term Well Integrity

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ABSTRACT

Well cement should provide structural support and zonal isolation through the entire service lifetime of a well. However, even if a good primary cement job is achieved, variations in temperature and pressure over the lifecycle of the well are likely to induce different failure mechanisms that threaten the set cement sealing integrity. This work presents an extensive finite element study with the aim to assess the relevance of casing-cement-formation material properties, geometric parameters and characteristic well-loading events, in contributing to the occurrence of cement sheath failure mechanisms. Special focus is given to thermal-related loading events. There is a discussion of main assumptions to describe and estimate the different cement sheath types of failure. A large number of test cases are defined on the basis of an automated sensitivity screening of random input properties of the wellbore components, in a conventional production casing section. The influence of casing stand-off positions and initial defects in the cement sheath are also evaluated. At the end of this paper, the approach is narrowed-down to be applied to a specific well case, in which the impact of transient well heating/cooling events on cement sheath integrity is assessed. Based on the results, guidelines for the assessment of long-term cement sheath integrity and selection of cement systems mechanical properties are given to mitigate the risk of losing zonal isolation.

1. Introduction

The aim of a primary cementing job is to provide zonal isolation and structural support to the wellbore. The success of the primary cement job begins with the proper placement of the cement slurry. This means that all cuttings and mud in the annulus are fully displaced. Mud channeling along the cement sheath adversely affects zonal isolation, as it provides a leak path for hydrocarbons (Tinsley et al., 1980). Casing centralization is also recognized as a main factor that influences the quality of the cement job (Jo and Gray, 2008; De Andrade et al., 2014).

After placement, cement setting properties have an important role in archiving zonal isolation. The cement curing process may be associated with shrinkage of the annular volume, which can lead to the initial development of cracks and debonding at the casing-to-cement and cement-to-formation interfaces. Therefore, obtaining a good cement job along the planned length of the casing string can be difficult to achieve. A well-formed annular cement sheath has very low permeability, meaning that no significant annular pressure or fluids migration can thus occur unless flow paths exist (Nelson and Guillot, 2006). Even if a proper annular cement sheath has proven to be acceptable by means of a pressure test and cement bond logs, the integrity of the bulk cement and bonding to casing and formation may be threatened as a result of cement deteriorating and changing downhole conditions over the well life cycle.

The study of how pressure and temperature variations affect the integrity of the cement sheath is important, as they occur frequently during normal completion and production operations. The occurrence of changing downhole stresses may exceed the set cement strength, and result in a loss of annulus isolation. Consequences of cement failure can be annulus pressure build-up and flow behind casings, therefore impacting the entire well integrity.

Due to the complex nature of cement type materials, experimental tests have recently become a relevant approach followed by several researchers to study the long-term capabilities of the annular cement sheath to withstand different loading scenarios during the well lifecycle. Goodwin and Crook (1990) conducted an experimental work to study the effect of pressure tests and high temperature on cement sheath failure. Radial cracks failures were predominantly observed. Carpenter et al. (1992) built special tests to evaluate the casing-cement bonding at elevated temperatures and pressures. They found that variations in pressure or temperature degrade bonding quality. Jackson and Murphey (1993)

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Nomenclature

E	Young's modulus
Cp	specific heat capacity
K	thermal conductivity
ΔP	pressure differential
ΔT	temperature differential
ID	inner diameter
OD	outer diameter
e	casing eccentricity
T_o	tensile strength
cem	cement
csg	casing
for	formation
Dbi	utilization factor for inner debonding
Dbo	utilization factor for outer debonding
RadCr	utilization factor for tensile radial crack
Shear	utilization factor for shear within bulk of cement

Greek letters

ν	Poisson's ratio
α	coefficient of linear thermal expansion
ϕ	internal friction angle
σ_3, σ_2, σ_1	east, intermediate and maximum principal stress
$\sigma_{m,2}$	effective mean stress
σ_R	radial stress
σ_H	hoop or circumferential stress
τ_{oct}	octahedral shear stress
τ_{max}	maximum allowable shear stress
ρ	density

performed similar experimental tests but focused on internal casing pressure changes. Among more recent studies, Boukhelifa et al. (2004) measured how annular cement cracked upon mechanical tensile loading, using an expanding load inside hollow cylinders of various cement mixtures. De Andrade et al. (2015a) performed experimental studies on scale down wellbore sections constituted of casing-cement-formation, upon temperature variations. Computed tomography monitoring revealed the propagation of debonded areas and cracks within the cement bulk due to the cyclic loading – mainly from initial cement sheath defects.

Experimental tests also provide a valuable input to validate numerical stress analysis tools (Bois et al., 2011). In that sense, cement sheath stresses, and failure mechanics, are estimated by either analytical or numerical models. However, it is recognized from the studies described above that there are still challenges associated with the reliability and efficiency of computer modeling when predicting annular cement sheath failure.

On the other hand, sensitivity analysis represents a good practice for assessing cement sheath performance (Laidler et al., 2007). Full variation of all parameters involved in the solid-mechanics model is, however, not attractive for designers as they come with excessive computational and time costs. It is therefore of interest to closely evaluate the influence of well architecture, mechanical and thermal parameters, in order to identify the key parameters for cement sheath failure estimates. This may assist to limit the extent of a sensitivity analysis, while still maintaining the reliability on the model estimates.

This paper presents a numerical study that aims to map the likelihood of cement sheath failure mechanisms towards variations in mechanical and thermal properties, as well as initial geometrical defects, for different well-loading events. Special focus is given to thermal-related loads. The test cases are given on the basis of a sensitivity screening of random input properties of the components in typical production casing well section. The numerical study is also expected to increase the understanding of the thermo-mechanical interaction of cased wellbore sections.

2. Annular cement sheath modeling

Conventionally, cementing engineers have had a strong focus on slurry design and following the best field cementing practices. As a result of evidence of fluid migration through the annulus that often occurring when wells age, there has been an increased concern about the long-term sealant integrity at an early stage of well design. Nowadays, for the prediction of stresses in the annular cement sheath, two-dimensional (2-D) mathematical models or simplified finite element analysis are often used by the industry. Still, this kind of approach is not routine in well design.

The accurate modeling of the annular cement sheath comprises complicated processes that occur during drilling, completion and production operations, which may impact the assessment of the cement integrity over the well lifecycle. As described by Gray et al. (2009), the stability of the wellbore, which influences the borehole geometry and formation stresses, should be first evaluated prior to placing the sealant in the annulus. Next, the second modeling phase involves the incorporation of casing and cement, which interacts with the formation to encounter a new structural equilibrium. At this stage, the set cement initial state is commonly uncertain and assumed/modeled by researchers in different ways. For instance, there is limited knowledge on the initial cement sheath stress state and geometry, casing-to-cement bond strength, filter-cake and interaction with the formation. Lastly, the operational loads and boundary conditions along the casing-cement-formation domain are applied, and the cement sheath integrity is assessed according to a selected failure criterion.

The first phase of modeling intends to define the shape and stress distribution around the borehole based on the in-situ stresses and the nonlinear material behavior of the rock. This brings more realism to the model but it is rather case dependent. The second phase involves a more challenging and complex phenomenon to be modeled, cement setting. Cement volume shrinkage/expansion during hydration may lead to residual stresses and flow paths such as micro-annulus or cracks/voids within the cement sheath. Moreover, cement mechanical properties will evolve as cement hydrates and aging. Different models have tried to represent this process. From semi-analytical models (Zhou and Wojtanowicz, 2000; Thiercelin et al., 1998a; di Lullo and Rae, 2000) towards more sophisticated Finite Element Analysis (FEA) as presented in Ravi et al. (2002), which imposes volume changes after cement has set, and lastly the approach introduced Bois et al. (2011) based on a fully coupled thermo-chemo-poro-mechanical model. Although these last models seem to better represent the initial stress characteristics of a casing-cement-formation well section, their application is limited by the availability of experimental data, both in terms of input parameters and validation tests.

Among the first to address the mechanical response of set cement, Thiercelin et al. (1998b) developed an analytical model for cylindrical casing-cement-formation well sections. They considered severe operational loads, and indicated that integrity of the cement sheath is a function of the geometry of the wellbore,