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A thermo-poroelastic analytical approach to evaluate cement sheath integrity in deep vertical wells

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ABSTRACT

Failure of cement sheath due to casing expansion or formations pressure during completion or production stages of HPHT or deep vertical wells is a very common phenomenon. There have been many studies providing approaches to predict cement sheath failure, where theory of elasticity or thermoelasticity together with the plane strain concept were taken into consideration to obtain representative results. However, sedimentary formations in subsurface layers are exhibiting a poroelastic behavior and theory of elasticity may not be able to fully describe their behaviors when changes in pore pressure and in-situ stresses are taking place. In this paper, an analytical approach based on the theory of thermoporoelasticity was presented to predict the possibility of cement sheath failure in deep structures. A separate numerical molding was also performed to evaluate the application of the approach developed. The results obtained indicated that a thicker cement can withstand a higher load applied by the formations and protect the casing against a significant collapse pressure. The temperature was also found as a significant contributor in increasing the pressure applied by the formation and casing on the cement due to pore fluid and steel expansions. Although some discrepancies observed between the results of the numerical simulation and the analytical model, it seems that the approach presented is able to provide reliable results considering the fact that interactions of material interfaces could not be included in the analytical modeling.

1. Introduction

Cement jobs are carried out to provide zonal isolations and protect the casing against the excessive pressure applied by formations during drilling and production. In fact, a poor cement job or cement failure during completion and production stages can easily result in casing damages, environmental contaminations, and partial or even total loss of wells (Bois et al., 2012). This kind of failure is often observed in high pressure high temperature (HPHT) or deep vertical wells where temperature and pressure can go up to 150 °C and 70 MPa respectively (Taoutaou et al., 2010).

There are generally two types of cement sheath failures including chemical degradations, taking place when cement is in contact with acids (Duguid, 2006; Barlet-Gouédard et al., 2006; Fabbri et al., 2009) or mechanical degradations, occurring when cement is under excessive compressive or tensile pressures (Boukhelifa et al., 2005). However, according to the field (Carey et al., 2007) and kinetics data analysis (Aiken and Wildgust, 2009), the chemical degradation is not a fast process and mechanical failures of cement should be considered as a primary concern during the life of a well.

There are, however, few models developed so far to evaluate the mechanical integrity of cement sheath during completion and production stages. For examples, Thiercelin et al. (1998a), (1998b) proposed analytical approaches for the cement sheath integrity analysis by assumptions of linear elasticity. This model was generalized by di Lullo and Rae (2000) to consider changes in mechanical properties of cement as a function of hydration. Thiercelin (2006) considered rocks, cement and casing as homogeneous isotropic linear elastic materials and used failure criteria to determine the cement mechanical integrity. Khandka (2007) did a study on the leakage behind the casing and developed an analytical approach to determine cement sheath failure based on theory of thermoelasticity. Li et al. (2010) recommended a mechanical model which could consider temperature and in-situ stresses in evaluation of cement integrity. Li et al. (2012) developed an analytical approach based on the old Kirsch equations to evaluate

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Nomenclature

r_a	Inside radius of casing
r_b	Inside radius of cement/outside radius of casing
r_c	Outside radius of cement/inside radius of formation
r_d	Outside radius of formation
P_i	Internal pressure of casing
P_{c1}	Contact pressure between casing and cement
P_{c2}	Contact pressure between cement and formation
P_i	External pressure of formation/far field stress
E_f, E_s, E_c	Young's modulus of formation, casing and cement respectively
v_f, v_s, v_c	Poisson's ratio of formation, casing and cement respectively
G_f	Shear modulus of formation
P_P	Pore pressure of formation
β	Biot parameter
ε_r, ε_θ, ε_z	Radial, tangential (hoop) and axial strains respectively
σ_r, σ_θ, σ_z	Radial, tangential (hoop) and axial stresses respectively
δ_{so}, δ_{ci}, δ_{co}, δ_{fi}	Deformation of casing outer interface, cement inner interface, cement outer interface and formation inner interface respectively
T	Temperature
α_f, α_s, α_c	Thermal expansion coefficient of formation, casing and cement

cement failure in arbitrary in-situ stress fields. They indicated the importance of considering the contact pressure in the interfaces of casing, cement and formations but did not provide any solution for it. Bui and Tutuncu (2013) developed analytical equations to evaluate cement failure in anisotropic in-situ stress conditions. They, however, did not mention anything about the interaction between casing, cement and formation by assuming that cement is subjected to the entire pressure applied by formations or casing. Yin and Gao (2015) developed analytical approaches to determine casing and cement deformations based on the contact pressure and thermoelastic equations. They assumed an elastic formation with a constant in-situ stress in their theoretical model. Teodoriu et al. (2010) and Xu et al. (2015) provided analytical solutions for mechanical failure of cement but neglected the poroelastic behavior of geological formations in their analysis. In fact, a linear elastic behavior is often assumed for geological formations when the cement integrity analysis is carried out. There have also been minor attentions to the importance of contact pressures when cement is under the pressure of casing and formations in its inner or outer interfaces.

The aim of this paper is to develop an analytical approach based on the theory of thermo-poroelasticity which can consider the effect of pore pressure and stress changes in determination of cement sheath failure in deep vertical or HPHT wells. The approach presented is able to consider the effect of pressure and temperature separately and would be applicable to even deep water wells where temperature may not be a critical contributor into degradation of cement integrity.

2. Cement sheath integrity

Recently, more HPHT and deep water wells are being drilled to supply the demand of energy. These wells are very well known for their pressures and temperature variations which may exceed 70 MPa and 150 °C, respectively. Cementing operations in these kinds of environments are challenging due to significant changes in physical and chemical properties of cements during the placement and after consolidation (Shadravan and Amani, 2012).

Having the cementing operation done, if there is no sign of fluid migration to the surface, it is assumed that properties of cement have been well designed to provide a short term zonal isolation. However, the long-term integrity of cement which is linked to its mechanical properties might still be a concern when it comes to drilling through very deep structures (Tahmourpour and Griffith, 2007). As a result, a systematic assessment of cement properties is crucial for marinating the integrity of wells during drilling and production stages.

There are generally three main mechanisms causing cement sheath failure during drilling or production stage including debonding, radial cracking, and plastic deformation (Ugwu, 2008). Debonding is often induced by cement shrinkage causing a weak bond between the cement and casing, or the cement and formations. Radial cracking is posed by the gradual formation of cracks in the cement due to fatigue or gradual increase of compression or tension loads. Plastic deformation, on the other hand, is referred to the situation where cements are permanently deformed under the pressure applied by surrounding formations and casings. Among these three mechanisms, radial cracking and plastic deformations are linked to the cement's elastic moduli (Bearden and Lane, 1961). For instance, the radial cracking often takes place when cements are stiffer than formations while plastic deformations are observed when cements are softer than rocks surrounding them (Bois et al., 2011). Debonding, however, frequently occurs due to loading and thermal stresses, poor mud removal, formation surface roughness, interface chemical interactions, hydration and chemical shrinkage (Ladva et al., 2005). Significant stress changes during the life of a well such as weight and temperature of drilling muds (Savari and Kumar, 2012), perforation of the casing (Lecampion et al., 2011), hydraulic fracturing (Lecampion and Prioul, 2013), reservoir acidization (Bois, et al., 2011), casing or formation integrity tests (Lee et al., 2004), production (Pickle and Swan, 2012), abandoned wells (Bai et al., 2015) and HPHT environment are among the reasons behind the loss of cement sheath integrity (Wang and Dahi Taleghani, 2014).

2.1. HPHT conditions

Conventionally, the oil and gas industry has focused on the short-term integrity of the cement which is essential for a good slurry mixing and placement. However, the long-term integrity which depends mainly on its mechanical and material properties must not be forgotten.

2.1.1. Temperature effects

A high temperatures environment affects the rheological parameters of the cement slurry and reduces its thickening time, thereby causing the cement sheath to set quicker which may cause creation of cracks in the cement due to a fast dehydration (Shadravan and Amani, 2012; Yetunde and Ogbonna, 2011). High temperature porous formations may apply more pressures on the cement than a low porosity formation due to the expansion of pore fluids. Very high temperatures may also change the crystalline structure of the cement causing reduction in its elastic and strength parameters. Stiles (2006) who did a study on the effect of ultrahigh temperatures on the mechanical properties of cement indicated that temperature increases the brittleness of cement making it more vulnerable to failure under high pressure