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Numerical simulation of the thermomechanical behavior of cement sheath in wells subjected to steam injection

Wendell Rossine Medeiros de Souza[a], Najib Bouaanani[b,*], Antonio Eduardo Martinelli[c], Ulisses Targino Bezerra[d]

[a] Petroleum Science and Engineering Post-graduate Program, Universidade Federal do Rio Grande do Norte (UFRN), Natal-RN 59078-970, Brazil, and Visiting Researcher, Department of Civil, Geological and Mining Engineering, Polytechnique Montréal, Montréal, QC H3 3A7, Canada
[b] Department of Civil, Geological and Mining Engineering, Polytechnique Montréal, Montréal, QC H3C 3A7, Canada
[c] Materials Science and Engineering Post-graduate Program, Universidade Federal do Rio Grande do Norte (UFRN), Natal, RN 59072-970, Brazil
[d] Civil Construction, Academic Unit 1, Instituto Federal da Paraíba (IFPB), João Pessoa, PB 58015-430, Brazil

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ABSTRACT

The exposure of oil wells to extreme conditions may lead to numerous problems associated with the loss of integrity of the cement sheath. A damaged cement sheath may result in fluid leakage and in some cases cause significant economic loss and environmental degradation. Thermal recovery processes are common techniques used to enhance oil recovery by submitting the materials to severe temperature gradients. However, this heating process induces thermomechanical stresses in the cement sheath which may lead to its cracking. This paper investigates the effects of cement slurry formulation on the thermomechanical behavior of cement sheath in wells subjected to the first heating phase of steam injection. For this purpose, three types of cement slurry formulations, one standard and two others with latex additions, were designed, mixed and tested in the laboratory to evaluate their mechanical properties. An axisymmetric finite element model was then developed and used to conduct a parametric study to investigate the thermomechanical response of oil wells with cement sheaths made of the various cement slurries, as well as the influence of applied temperature gradients, heating durations and formation stiffness. The results mainly show that issues of cement sheath integrity under steam injection are generally localized in the region near the formation, and that they are closely related to the heating phase of the well. It is also found that combining the use of a more flexible and expansive cement slurry formulation with the slow application of temperature gradient generally improves cement sheath integrity during steam injection. These beneficial effects were shown to be more effective for stiffer rock formation and larger applied temperature gradients.

1. Introduction

It is increasingly important to develop safer, environmentally and cost-effective technologies to satisfy the growing demands in a context of decreasing oil resources. The high-viscosity of heavy oil, in its natural state inside underground reservoirs, complicates its flow towards the surface. Therefore, nonnegligible quantities of oil can be lost as they are retained within the components of traditional exploitation and production systems. Recovery techniques are then usually required to improve the efficiency of oil extraction (Nelson and Guillot, 2006; Garnier et al., 2010; Alvarez and Han, 2013). Among these techniques, steam-based recovery processes such as cyclic steam injection, steam-flooding, and steam-assisted gravity drainage are widely used (Nelson and Guillot, 2006; Alvarez and Han, 2013; Guo et al., 2015). Steam injection has been first applied in the late 50's and has since been recognized worldwide for being cost-effective, with a relatively high success rate in reducing the high viscosity of heavy oil and increasing gas expansion (Alvarez and Han, 2013). As illustrated in Fig. 1, this technique consists of three stages: injection, soaking and production. First, steam is injected into the well for a certain duration that could reach 20 days to heat the oil in the surrounding reservoir. Steam injection is then stopped and the well is shut down for up to 10 days to allow heat transfer to oil. This process can be repeated at intervals of 6 months to one year depending on the specific conditions of each well (Nelson and Guillot, 2006; Paiva, 2008; Alvarez and Han, 2013; Guo et al., 2015). The steam temperature may easily exceed 200 °C and

* Corresponding author.
E-mail addresses: wendell@ufersa.edu.br (W.R. Medeiros de Souza), najib.bouaanani@polymtl.ca (N. Bouaanani), martinelli.ufrn@gmail.com (A.E. Martinelli), dartarios@yahoo.com.br (U.T. Bezerra).

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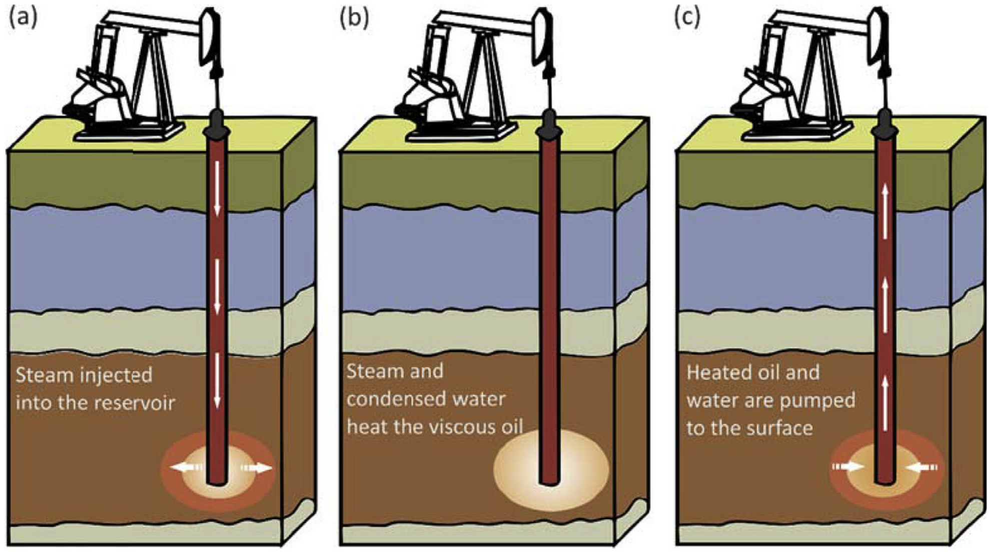

Fig. 1. Process of cyclic steam injection: (a) injection; (b) soak; and (c) production [Adapted from Alvarez and Han, 2013].

could reach 350 °C, under pressure that could reach 6 MPa (Placido et al., 1997; Dean and Torres, 2002; Alvarez and Han, 2013). The heating process generated by steam injection can induce extreme thermal stresses in the well, which, when combined to mechanical stresses, may cause: (i) plastic yielding and/or buckling of the steel casing (Placido et al. 1997; Peng et al., 2007; Li, 2008; Ferla et al., 2009), and (ii) cracking or failure of the cement sheath and/or its debonding from the casing and surrounding rock formation (Dean and Torres, 2002; Garnier et al., 2010; De Bruijn et al., 2010; Teodoriu et al., 2013; Yuan et al., 2013; Wang and Taleghani, 2014; Lavrov et al., 2015; Shadravan et al., 2015; Ichim et al., 2016). A damaged cement sheath can favor leakage of hydrocarbonates to the rock formation, where they may propagate through geological strata to reach aquifers or the surface, thus causing significant environmental degradation, and calling for expensive remedial measures (Thiercelin et al., 1998; Nelson and Guillot, 2006; Bellabarba et al., 2008; Dusseault and Jackson, 2014; Lavrov et al., 2015; Zhang et al., 2015; Abimbola et al., 2016). This environmental impact adds to the economic loss associated with production inefficiency due to oil lost (retained) in wells with damaged cement sheaths. Therefore, studying the factors that might influence on the cement sheath mechanical integrity is of great significance to reduce the risk of cement sheath failure (Vignes, and Aadnøy, 2010; Zhang and Wang, 2017).

Several cement slurry formulations (Cain, 1966; Goodwin and Crook, 1992; Carpenter et al., 1992; Dean and Torres, 2002; Myers et al., 2005; Boukhelifa et al., 2005; Stiles, 2006; Bezerra et al., 2011; Tomilina et al., 2012; Teodoriu et al., 2013; De Andrade et al., 2014; Albawi et al., 2014; Pernites and Santra, 2016; Bu et al., 2017) have been studied to improve the mechanical behavior of cement sheaths in oil wells. Such studies revealed the great influence of the thermo-mechanical properties of the casing, the cement and the formation on damage occurring within the cement sheath.

Strength, flexibility and thermal properties have been pointed out as key issues (Thiercelin et al., 1998; Bosma et al., 2000; Dean and Torres, 2002; Myers et al., 2005; Stiles, 2006; Tomilina et al., 2012; Yuan et al., 2013). Such mechanical properties can be enhanced by mixing the cement slurry with various additives (Pedersen et al., 2006; Pernites and Santra, 2016; Broni-Bediako et al. 2016), and in particular with latex, which has been shown to be promising for this purpose (Dean and Torres, 2002; Pavlock et al. 2012). However, more research is still needed to optimize latex-based slurry formulations. The durability of the cement sheath can also be affected by the mechanical properties of the formations in which the well is drilled (Bour, 2005).

Several approaches have been proposed to study the stress field in wellbores and their structural integrity under downhole conditions, either based on analytical formulations (*eg.* Thiercelin et al., 1998; Li et al., 2010; Bui and Tutuncu, 2013; Wang et al., 2016; Zhang et al., 2015; Liu et al., 2017; Zhang and Wang, 2017), or numerical simulation (*eg.* Ravi et al., 2002; Shahri et al., 2005; Gray et al. 2007; Ferla et al., 2009; Fleckenstein et al., 2001; Shen and Beck, 2012; Bai et al., 2015; Guo et al., 2015). However, only few research coupled the analytical or numerical model predictions of the behavior of wellbores to the experimental investigation of slurry formulations of cement sheaths. The thermomechanical effects of steam injection on the integrity of latex-based cement sheaths have also been rarely addressed.

This paper focuses on investigating the effects of the first heating phase of steam injection on the thermomechanical behavior of cement sheath in a wellbore considering different experimentally characterized cement slurry mixtures (expandable and flexible cements), including new latex-based formulations. The influence of temperature gradients, heating durations, and rock formation stiffness are studied through several case studies. The paper is organized as follows. First, the basic assumptions and details of the adopted numerical models are provided. Then, various case studies are presented, followed by the discussion of the obtained results.

2. Basic assumptions and finite element models

This section describes the finite element models used to investigate the distribution of temperatures and stresses in the main components of a simplified oil well, i.e., a steel casing, a cement sheath, and the surrounding rock formation, as illustrated in Fig. 2. An axisymmetric finite element model is developed considering the axisymmetry of the problem around the center of the wellbore, i.e., geometry, boundary conditions, and applied loads. The modelled zone, illustrated in Fig. 3, has a thickness e, a radius and is located at a distance H from the surface of the oil well. The internal and external radii of the cylindrical steel casing are denoted as r_i and r_e, respectively, and the thickness of the cement sheath as a. A large ratio between the model radius and that of the wellbore is considered to simulate infinite boundary conditions far from the wellbore (Ferla et al., 2009). Boundary conditions are applied to restrain vertical displacements at the top and bottom surfaces of the modelled zone, as well as horizontal displacements at the far limit of the rock formation (Ferla et al., 2009). Initial stresses are applied to account for overburden pressure in the modelled zone (Guo et al., 2015). A transient thermal analysis capable of updating temperatures