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Performance evaluation of swelling elastomer seals

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ABSTRACT

Swell packers are now being widely used for increased recovery from difficult oil and gas reservoirs and for remediation of various well problems. It is important to know how the elastomer actually swells in a particular well, how much time is required to achieve sealing, and what sealing pressure is generated. No published work is available that numerically investigates elastomer seal performance based on actual material properties at various stages of swelling. Current work uses finite element simulation to investigate swelling elastomer seal behavior in downhole petroleum applications. Variations in sealing pressure are studied for seal length, seal thickness, compression ratio, water salinity, swelling time, and type of well completion. Month-long swelling experiments on samples of two actual elastomers provide input to the numerical model in terms of real material and deformation data. Contact pressure was found to increase with swelling, at a higher rate in the first few days, then more slowly. Higher sealing pressure was observed in the case of swelling in lower-salinity brine, larger length of the sealing element, higher compression ratio of the seal, and elastomer swelling against rock formation as compared to steel outer-casing. These results can help field engineers decide which swelling elastomer and what seal configuration to use under a given set of field parameters. The study can also be used by application designers and academic researchers as a starting point for swelling elastomer based seal design and analysis.

1. Introduction

In the last few decades, petroleum drilling and development has witnessed the advent of new technologies such as horizontal drilling, multi-stage fracturing, and novel methods of reservoir management. Use of the traditional method of cementing "in place" can reduce productivity by largely covering up the sand face in a horizontal well. Move towards non-cemented completions required some sort of an open-hole packer. One solution was mechanical packers with hydraulic actuation, providing an annular seal between the production casing and the rock formation. In unconventional reservoirs, or in cases such as slotted liners, pressure buildup for packer setup is not only difficult but at times impossible. This led to the development of *swellable packer*, which consists of rubber elements that swell in a hydrocarbon, establishing a seal between the body of the packer and the outer casing (PetroWiki, 2015). Operational simplicity is a major benefit of swellable packers, leading to significant savings in cost and time. No moving parts are required, eliminating the necessity for application of hydraulic pressure or manipulation of the tubular, also doing away with the need for special service personnel. After being simply run to depth, the packer keeps on swelling, finally forming a differentially sealing annular barrier. Production or injection operations can now be started (Rigzone, 2015; Kennedy et al., 2005). Swelling elastomers can be designed to swell either in oil or in water, depending on the nature of the required application. Schematic arrangement of the elements of a swell packer is shown in Fig. 1.

After drilling for the well, a swellable packer is positioned in the wellbore with a pre-determined separation between the elastomer and the outer casing (or the formation). After coming in contact with the swelling fluid, free swelling of the elastomer takes place until the packer-formation gap is filled up (Akhtar et al., 2013; Qamar et al., 2009; Rogers et al., 2008). As the elastomer swells further, sealing pressure is generated at the contact surface. An effective seal is created when contact pressure developed through swelling becomes large enough to overcome the differential fluid pressure across the seal ends. Swell packers can be effectively used under both well completion strategies. In an openhole well type, the rock formation is in direct contact with the sealing element. In the case of a cased-hole, the swelling elastomer butts against the outer steel casing. Placement of swell packers for zonal isolation in a horizontal well is shown in Fig. 2 (Advanced Wells, 2015).

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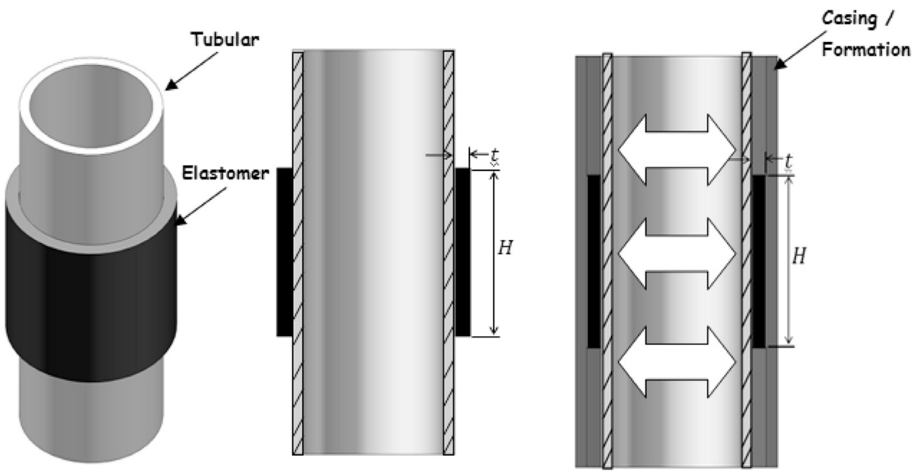

Fig. 1. Arrangement of inner steel tubular, elastomer, and rock formation in a typical swellable packer arrangement.

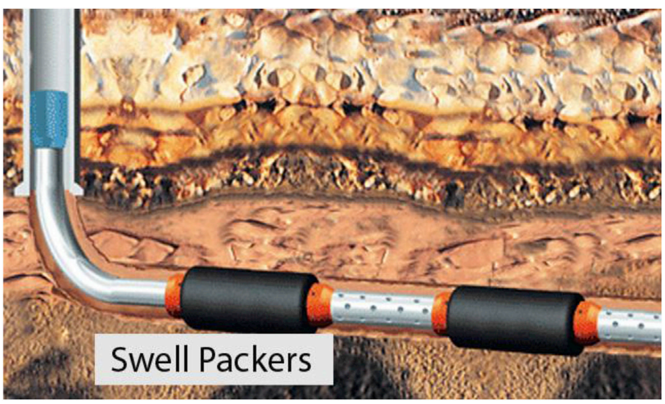

Fig. 2. Use of swell packers for zonal isolation in a horizontal well (Advanced Wells, 2015).

Analytical models for swelling of rubberlike materials (Al-Hiddabi et al., 2015; Al-Kharusi et al., 2013; Al-Kharusi et al., 2011) are difficult to formulate, and restricted in actual application due to their need for simplifying assumptions. Laboratory tests for material behavior of swelling elastomers cannot replicate in-situ conditions, and cannot be run for all required parameters. However, experimental evaluation of material behavior of swelling elastomers under different conditions is essential for analytical and numerical modeling. Experimental work on swelling behavior of elastomers, using saline water and crude oil as swelling media, has been carried out by different investigators (Qamar, 2017a, b, Qamar et al., 2016, Qamar et al., 2015, Pervez et al., 2012, Qamar et al., 2009). Tensile properties of elastomers in different swelling media and at different temperatures have been reported by Qamar and Pervez (2017), Qamar et al. (2012), and Akhtar et al. (2012). Compression and bulk behavior of water-based and oil-based swelling elastomers has been studied by Qamar (2016), Qamar et al., 2013a, b, and Akhtar et al. (2012). These elastomers are often used in conjunction with solid expandable tubulars (SETs) in petroleum applications. Tensile testing of expandable steel tubulars has been conducted by various researchers (Al-Abri et al., 2016, Khan et al., 2016, Qamar, 2017a, b, Qamar and Pervez, 2014a, b).

Though time-consuming to run under all possible conditions, properly developed and robust numerical models can be used to predict near-actual performance of elastomeric seals. Alzebdeh et al. (2010) conducted finite element analysis of elastomer seal used in tandem with solid expandable tubular (SET) applications. Material properties used for the simulation were for an elastomer in the initial unswelled state. Behavior of contact pressure was studied for variations in length, thickness, and compression ratio of the elastomer seal, expansion ratio of the steel tubular, and type of formation (rigid, elastoplastic, etc). Finite element method was used by Qamar et al., 2013a, b to investigate the changes in bulk, compression, and structural properties of an elastomer due to swelling. Simulations were based on elastomer properties experimentally determined under different conditions and at different stages of swelling. The investigation covered effect of swelling and water salinity on elastic, shear and bulk moduli, Poisson's ratio, polymer cross-link chain density, and chain average molecular weight of the elastomer material.

1.1. Current work

Deployment of swell packers for various applications in petroleum drilling and development has resulted in significant savings in time and cost. However, a hit-and-trial strategy can also lead to rather costly failures. Full-scale laboratory tests under actual field conditions are either not possible, or extremely difficult and cost-prohibitive. Numerical modeling and simulation, properly verified by a few well-designed experiments, is the only viable assessment method before deploying elastomer seal elements into oil and gas wells. Finite-element analysis (FEA) of the performance of swell packers (swelling elastomer seal element vulcanized over steel tubular) is presented in this paper. Variation of contact pressure has been investigated for different seal parameters and well conditions (length and thickness of seal element, compression ratio, water salinity, swelling time, and open-hole or cased-hole type of well completion). No such study is currently available in published literature, numerically modeling seal behavior for actual elastomer and tubular materials, under real well conditions. Results presented here are useful for proper selection of swell packers for different wells, and for design improvement of elastomer seals and their applications.

2. Hyperelastic modeling of rubberlike materials

Most continuum mechanics treatments of rubberlike materials begin with the assumption that rubbers and elastomers are hyperelastic and isotropic materials (Gent, 2012). A hyperelastic material model is a type of constitutive relation for rubbers in which deformations (such as those due to swelling) are defined in terms of principal stretches λ_i. The major hyperelastic material models are briefly described below.

One major approach used to describe the deformations in elastomer chains follows Gaussian statistics, wherein a chain never approaches the maximum stretch. It is therefore limited to almost linear material response (small to moderate stretches). Neo-Hookean model (Boyce and Arruda, 2000) is an example of this approach, defining the strain energy function as