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Impact of hydraulic fracturing on cement sheath integrity; A modelling approach

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ABSTRACT

Recent arguments about the possibility of well leakage and underground water pollution in particular regions have raised significant concerns regarding wellbore integrity during hydraulic fracturing in shallow formations. In this paper, we take a look at the containment of annulus cracks that might develop during hydraulic fracturing treatments. Wellbore integrity is highly dependent on the integrity of the bonding between the cement and the formation as well as the bonding between casing and cement. Cement heterogeneity results from unsmooth borehole surfaces, complex geological conditions, mud cakes, and cement contamination. Excessive fluid pressure during hydraulic fracturing not only provides the driving force for the initiation and propagation of fractures in the reservoir, but also in special cases, it may lead to fracture propagation around the casing, i.e. annulus cracks. A coupled three-dimensional poroelastic model with embedded cohesive zones is introduced here to simulate different fracture propagation scenarios that may occur in vertical and horizontal wells during hydraulic fracturing stimulations in cased-hole zones. The cohesive layer theory is utilized to model the initiation and propagation of transverse, longitudinal and delamination fractures. Using the numerical analysis provided in this paper, a few hydraulic fracturing cases were simulated by taking advantage of the treatment pressure data and petrophysical logs, and the results were compared with the post-treatment radioactive tracer logs available for these wells.

1. Introduction

Wellbore integrity can be endangered during hydraulic fracturing treatment due to the occurrence of excessive fluid pressure and large fluid pressure fluctuation at perforations. Hence, investigating the possibility of developing annulus fractures may have a significant importance on preventing any possible underground water pollution. Three types of fractures may develop in hydraulic fracturing treatments: annulus failures, transverse fractures, and longitudinal fractures. Annulus fractures occur in cylindrical shapes around the casing, which could be induced by a large treatment pressure or by large fluctuations in the treatment pressure, especially in cases of low confining stress or poor cement quality (Behrmann and Nolte, 1998; Lecampion et al., 2011). Fracture propagation along the casing exterior not only breaks well integrity but it also dehydrates the fracturing fluid and in extreme cases it may cause near-wellbore screenout. The main focus in this research is investigating the likelihood of annulus fracture containment versus uncontrolled development. Similar cylindrical failure geometry exists in different engineering problems like fiber reinforced composite materials (Ozbek and Erdogan, 1969; Close and Zbib, 1996). There have been efforts in calculating the stress intensity factor and the opening of the cylindrical fracture under uniform loading (Farris et al., 1989; Zbib et al., 1995) or in the presence of inhomogeneities (Li et al., 2001), but the authors did not find any analytical or numerical solution for fluid-driven cylindrical fractures in the literature (e.g. Dahi Taleghani and Klimenko, 2015; Tabatabei and Dahi-Taleghani, 2016). The inherent cylindrical geometry of wellbores and weakness of cement sheath mechanical properties, due to heterogeneities, may assist the initiation of annulus fractures at the same time, when fractures are growing in the formation. Historically, due to a major concentration of fracturing treatments in large depths, the confining in situ stresses were large enough to prevent any uncontrolled growth of fractures. Additionally, limiting fracturing jobs to single stage jobs reduced the likelihood of a large number of pressure fluctuations in a treatment well to cause progressive damage. Currently, utilization of hydraulic fracturing treatments in

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shallow formations and the popularity of multistage stimulation techniques make revisiting this problem beneficial to ensure the safety of fracturing operations. Since the outcome of these integrity problems is most likely underground venting and it may not lead to any fluid flow to the surface, the integrity problem is hard to identify and may stay hidden for long periods of time without any implications unless it reaches the aquifers.

Common fracture geometries considered in hydraulic fracturing simulations are longitudinal and transverse fractures, which have failures planes reaching into the formations. Both types of fractures may concurrently develop delamination fractures between the casing and the formation due to excessive fluid pressure behind the casing. Transverse fractures are perpendicular to borehole axis while longitudinal fractures are parallel to borehole axis. In general, fractures have a tendency to propagate along the direction that is perpendicular to the minimum principal stress, however, friction at the perforations, misaligned perforations and perforation at the inclined part of the wellbore may lead to the formation of fractures which are not normal to the minimum in−situ stress, at least close to the wellbore. Development of microannulus or annulus cracks may greatly facilitate fluid flow at the mouth of transverse fractures and, in some cases, help the transition of fracture geometry from transverse to longitudinal or vice versa. Lecampion and Prioul (2013) showed the potential role of differential stresses caused at different injection rates on reorienting stresses around the wellbore and their consequent effect on the development of longitudinal fractures versus transverse fractures in horizontal wells. Minimizing the likelihood of annulus fracture formations would reduce the loss of fracturing fluid and divert it into the direction that facilitates further fracture penetration into the reservoir, which improves the effectiveness of stimulation treatments and maintains wellbore integrity after hydraulic fracturing.

To predict different modes of failure involved in hydraulic fracturing and their consequent effects on wellbore integrity, common fracture assessment tools like tiltmeter or microseismic tools cannot be employed. The main tools for monitoring annulus cracks are cement bond logs, tracer-logs, and distributed temperature logs, which all are post treatment assessment tools with limited capability to provide fracture geometry at the wellbore only. Hence, modelling may help us to predict these problems or more reliably conduct post-treatment assessments on the dimension of annulus cracks. The tracer log shown in Fig. 1 is typical available data to investigate failure characteristics during hydraulic fracturing. The concentration of tracers confirms the opening of a fracture behind the casing, but not the type of the failure. The “Yellow” and “Red” represent tracers pumped in the first and second phase during the treatment, respectively. The reasons for fracture growth in non-perforated zones could be, but not limited to, fracture height growth or casing/cement integrity problems.

Although field evidence like tracer logs gives us an important starting point to speculate about possible problems and build the simulation, in general tracer-logs and other field measurements are post-treatment failure assessments without any predictive capability. Their high costs further limit their wide application. Compared with field tests, the laboratory tests are easier to be conducted in the lab (Abass et al., 1996; Van de Ketterij and de Pater, 1999). However, the limited laboratory conditions cannot represent the real wellbore condition. To overcome these limitations, numerical simulations provide a way to investigate and predict wellbore integrity problems. The longitudinal and transverse fractures as well as their competition in terms of mechanical and geometrical aspects have been studied by using linear elastic strength criteria (Lecampion et al., 2011) and cohesive zone method (Carrier and Granet, 2011). However although, available models are capable of investigating the longitudinal and transverse fractures

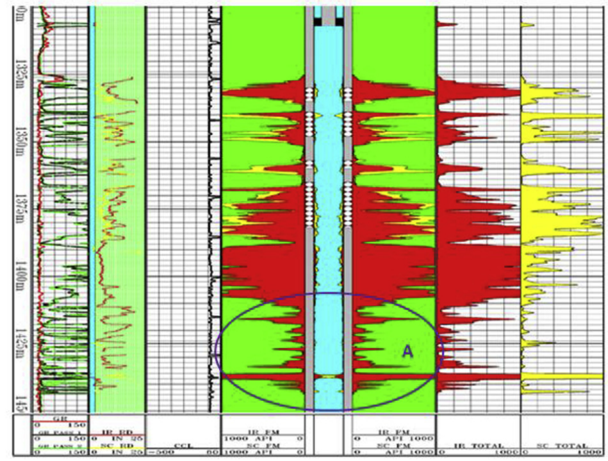

Fig. 1. Tracer log of a stimulated well. Longitudinal (or axial) and transverse fractures are detected around an inclined well based on the tracers concentration. The tracers are presented by yellow color for the first phase and red color at the second phase. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

around the wellbore during hydraulic fracturing stimulation, the consideration of annulus failure and wellbore integrity involved in this process is missing.

This works aims at redefining the classical cohesive zone models for hydraulic driven fractures. The main difference between proposed theory and the classical cohesive zone models is that the coupling effects between pore fluid and solid skeleton of porous rocks are considered in the developed theory, while in the case of classical cohesive models the conventional traction-separation laws are used to describe the fracture. In other words, the pore fluid pressure is considered the main driving force for the fracture herein that provides a more realistic description for the physics behind the hydraulic fracturing. In this paper, a coupled three-dimensional poroelastic model is developed which is capable of simultaneously modelling initiation and propagation of transverse, longitudinal and annulus failures. The potential failure zones are represented by pre-inserted cohesive elements with the bilinear traction separation law as the failure criterion. Excessive fluid pressure during hydraulic fracturing would provide the driving force for fracture propagations. The comparison between failure patterns from numerical analysis and field measurements, i.e. Radioactive tracer-logs, are used to provide a qualitative benchmark for the model. The developed method could be a predictive tool for the assessment of cement sheath integrity before hydraulic fracturing treatments. In this paper, we performed a comprehensive analysis on hydraulic fracturing and its concomitant wellbore integrity problems. Four different scenarios are selected for analysis: 1) delamination fracture in vertical wells stimulation; 2) delamination cracks in vertical section of the wellbore due to leakage at the casing shoe; 3) delamination cracks in horizontal wells by taking into account the influences of formation and cement heterogeneity; and 4) delamination fractures in inclined wells. In the case of initiation of delamination cracks around the casing, the length of the debonded zone and its containment is discussed based on the results of the numerical model.

2. Governing equations

In sake of brevity, the governing equations are outlined herein. The interested reader may refer to (Detournay and Cheng, 1991; Shojaei et al., 2014) for a thorough discussion on proelasticity and