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Mitigating lost circulation: A numerical assessment of wellbore strengthening

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ABSTRACT

Drilling in complex geological settings often possesses significant risk for unplanned events that could potentially impede already cost-demanding operations. Lost circulation, a major challenge in well construction, refers to the loss of drilling fluid into formation during drilling operations. When excessive wellbore pressure appears, lost circulation is induced by tensile failure or reopening of natural fractures at the wellbore. Over years of research efforts and field practices, wellbore strengthening techniques have been successfully applied in the field to mitigate lost circulation and have proved effective in extending the drilling margin to access undrillable formations. In fact, wellbore strengthening contributes additional resistance to fractures so that an equivalent circulating density higher than the estimated fracture gradient can be exerted on the wellbore.

In this study, a fully coupled hydraulic fracture propagation model based on the cohesive zone model is presented. By implementing the model, an extensive parametric study is conducted to investigate factors involved in lost circulation. The parametric influences emphasizing the mass balance within the fracture reveal mechanisms of lost circulation mitigation. Simulation studies on wellbore strengthening are conducted in two parts, hoop stress enhancement and fracture resistance enhancement. First, a near-wellbore stress analysis characterizes wellbore mechanical responses during lost circulation. The results show elevated hoop stress during fracture width development, which validates the hypothesis of hoop stress enhancement. Also, beneficial influences from poroelastic effect and high rock stiffness are demonstrated. Then, a novel method to simulate fracture sealing is introduced to quantify fracture gradient extension for field practices. With this method, a case study on fracture sealing investigates the roles of sealing permeability and sealing length. The results show inhibition of fracture repropagation and conclude that fracture tip protection is achieved through fracture sealing and fracture fluid dissipation. From the case study, operational insights on wellbore strengthening design are derived.

1. Introduction

The mud weight window (MWW) compels the annular pressure profile by a lower limit to prevent fluid influx and wellbore instability and by an upper limit (i.e., fracture gradient) to avoid wellbore breakdown and lost circulation (Zhang et al., 2008). A narrow MWW commonly appears in drilling depleted reservoirs where fluid production reduces the fracture gradient and extended-reach wells with large annulus pressure fluctuation. Drilling in the above settings is often plagued with lost circulation and its chain reactions (e.g., wellbore instability, underground blowout, unplanned casing point, etc.), causing protracted nonproductive time and exorbitant expense to remediate the issues (Cook et al., 2011).

Lost circulation is caused by unintentional hydraulic fracturing of a wellbore. Excessive wellbore pressure (i.e., annular pressure) can originate from surge effect, annulus pack-off, high annulus friction losses, etc. When wellbore pressure exceeds fracture initiation pressure (FIP) and fracture propagation pressure (FPP), hydraulic fracturing is induced (Feng et al., 2016); then, drilling fluid invades the induced fracture and is lost into the formation. For an intact wellbore, FIP at the wellbore can be higher than far-field FPP because its circular geometry magnifies the in-situ stresses into a more compressive form (Hubbert and Willis, 1957). However, if fractures are induced or natural fractures exist, the wellbore fails when wellbore pressure equals FPP (Lee et al., 2004). Therefore, to prevent lost circulation for a fractured wellbore, fracture gradient is governed by FPP. In complex drilling environments, limited casing points

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exist in order to reach the target depth so that necessary mud weight reduction at a hole section is constrained by the subsequent drilling plan. Hence, mitigating lost circulation, which aims for widening the MWW, is essential for the well-being of drilling operations.

Wellbore strengthening (WBS) techniques have been widely practiced. From field observations, WBS can improve resistance to the induced or natural fracture so that the wellbore can sustain the equivalent circulating density (ECD) higher than the estimated fracture gradient. In general, current WBS techniques originate from two hypotheses: hoop stress enhancement method (e.g., the stress cage) and fracture resistance enhancement method (e.g., the tip screen-out). Nevertheless, in all of the techniques, lost circulation material (LCM) is added into drilling fluid and is engineered for particular sizes and mechanical properties based on the predicted fracture geometry. Upon circulating to the fractured depth, LCM is expected to deposit within the fracture and form a particle aggregation (or immobile mass). Since LCM is carried by the mud, dehydration of the aggregation dictates the success of WBS. For this reason, WBS in permeable formations (e.g., sandstone) is more effective than in low-permeable formations (e.g., shale). Lost circulation issues in fractured or vugular formations (e.g., carbonate) can be extreme cases, where applying WBS is impractical or uneconomical (Masi et al., 2011). Therefore, this paper only speaks to lost circulation issues in clastic rocks such as sandstone and shale.

The purpose of the hoop stress enhancement method is to modify the local compressive hoop stress. Hoop stress is the tangential stress with respect to wellbore circumference. A fracture at the wellbore is essentially held closed by compressive hoop stress. Applying displacement at the fracture surface builds the hoop stress, which in turn raises the required wellbore pressure to reopen the fracture and extends the margin of ECD (as shown in Fig. 1). With this objective, the immobile mass (formed by the dehydration of particle aggregation) intends to prop the fracture.

Alberty and McLean (2004) introduced the stress cage model. A stress cage projects that LCM deposits near the fracture mouth, acting as a proppant to modify the hoop stress in the near-wellbore region and as a seal to isolate a fracture from wellbore pressure. Dupriest (2005) presented the fracture closure stress (FCS) model. Different from the stress cage model, the FCS model seeks stress modification on a longer scale along the fracture. Additionally, this model emphasizes tip isolation, enhancing the resistance of fracture propagation. Theoretical studies have found that hoop stress can be significantly increased in the vicinity of particle aggregation and have underlined the strong influence of in-situ stress anisotropy, propping location, and formation rock stiffness (Alberty and McLean, 2004; Wang et al., 2007, 2009; Morita and Fuh, 2012; Feng et al., 2015; Mehrabian et al., 2015; Zhang et al., 2016, Zhong et al., 2017). Field observations have also shown the improvement of a wellbore's pressure-sustaining capability after treatment (Aston et al., 2004; Dupriest, 2005; Song and Rojas, 2006; Aston et al., 2007).

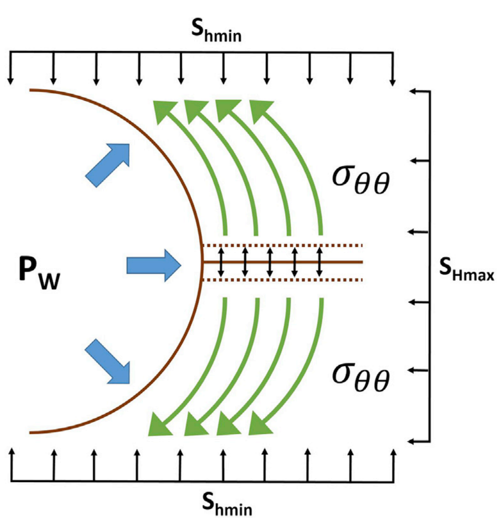

Fig. 1. A schematic of hoop stress enhancement for half of the wellbore. The dotted line indicates the displacement of the fracture surface after enhancement.

The objective of the fracture resistance enhancement method is to raise the apparent FPP (noting that fracture repropagation occurs after the reopening). In this method, the immobile mass acts as a sealant, which prevents wellbore pressure from transmitting to the fracture tip (as shown in Fig. 2). In theory, the opening and the propagation of a hydraulic fracture is governed by the net pressure, which is fracture fluid pressure minus the minimum in-situ stress (Yew and Weng, 2014). As immobile mass inhibits fluid flow across, the net pressure in the vicinity of the tip is reduced. Thus, the fracture propagation is suppressed.

The DEA-13 project conducted by the Drilling Engineering Association pioneered the fracture resistance enhancement method (Morita et al., 1990, 1996; Onyia, 1994). From their experiments, a mud dehydrated zone was observed in the vicinity of the tip, and water-based mud fracturing presented higher FPPs than oil-based mud. The dehydrated zone is believed to isolate the fracture tip from the wellbore pressure, restricting the propagation until fluid breaks through the immobile mass and pressurizes the fracture tip. Hence, a better dehydration capability of LCM contributes to higher FPPs in water-based mud fracturing. Fuh et al. (1992, 2007) presented the tip screen-out model with mathematical descriptions and field trials. Kaageson-Loe et al. (2009) investigated the fracture sealing capability of particulate-based LCM and detailed a fracture-sealing-mechanism hypothesis. van Oort et al. (2011) proposed the fracture propagation resistance model. Since particle aggregation yields a low permeability when it is poorly sorted, many experiments found that optimum particle-sized distribution exists in elevating the FPP (van Oort et al., 2011; Razavi et al., 2015). Guo et al. (2014) stated that preventive treatment with low-concentration LCM is more effective than remedial treatment with higher concentration.

Previous WBS studies have contributed considerable knowledge for the drilling community. Due to the complexity of bottomhole conditions, simplification must be applied in the model for field implementation. In previous hoop stress enhancement studies, assumptions have often been made on linear elastic rock properties and predefined fracture length (Alberty and McLean, 2004; Wang et al., 2007; Morita and Fuh, 2012; van Oort and Razavi, 2014; Feng and Gray, 2016). Even though these assumptions offer quick assessment for WBS operations, they might underestimate the fracture gradient extension without considering the pressure dissipation within the fracture. In addition, experimental and field observations presenting enhanced pressure-containing capability after WBS treatment are independently explained with very different concepts and lack quantitative validations. However, it might be too difficult to perform real-time monitoring in a laboratory or at a field to detect, for example, the fracture reopening and dehydration location inside fracture. Therefore, the fundamental mechanisms of WBS are still in dispute within the industry.

In this paper, a fully coupled hydraulic fracturing model based on the cohesive zone model (CZM) is presented. The model explicitly simulates the dynamic process of fracture growth during lost circulation, along with mechanical wellbore behaviors. By utilizing the model, an extensive parametric study is conducted to investigate drilling-induced fractures under various rock properties and bottomhole conditions. Inspecting parametric influences pinpoints the controllable factors impeding fracture growth, which are believed to serve principal roles in WBS treatment. This paper also aims to validate the proposed hypotheses of WBS. First, hoop stress enhancement is validated by comparing wellbore mechanical responses during fracture propagation. Then, a novel simulation method is introduced that integrates fracture resistance enhancement (i.e., fracture sealing for tip protection) into the hydraulic fracturing simulation. This method explicitly accounts for the dynamic diffusion across the immobile mass, captures the time-dependent responses of an induced fracture, and offers the capability of quantifying the fracture gradient extension for drilling operations. Lastly, a case study on fracture