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An integrated fluid flow and fracture mechanics model for wellbore strengthening

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ABSTRACT

Fracture-based wellbore strengthening techniques are preventive methods that can reduce the cost of lost circulation and non-productive time. The mud weight window can be extended by plugging fractures with wellbore strengthening materials (WSM) in the near-wellbore region. To maximize the strengthening effect, accurate fracture geometry prediction is of critical importance to the design of WSM. This paper presents a novel, coupled fluid flow and fracture mechanics model for wellbore strengthening applications that accounts for near-wellbore-induced fracture behavior. For fluid flow, mass conservation is considered and momentum conservation is examined; the latter shows that pressure loss with near-wellbore fracturing is low. Thus, we can neglect the pressure drop in the fractures and assume the fluid pressure inside the fractures is equal to the wellbore pressure. The pressure-width relationship (rock elastic deformation) and stress intensity factor are obtained by a dislocation-based approach. For the fracture propagation criterion, the calculated stress intensity factor is compared with fracture toughness at each time step.

The stress intensity factor and fracture reopening pressure (FROP) are verified with Tada's model and Feng's model, respectively. Then, simulation results are compared with the large leak-off solutions of the Perkins-Kern-Nordgren (PKN) fracture model. The simulation results reveal that the PKN model overestimates the fracture mouth width, fracture length, and wellbore pressure. Furthermore, the simulation results of wellbore pressure show a different trend. Therefore, we cannot directly use the PKN model to design wellbore strengthening applications. The main reason is the presence of wellbore can generate near-wellbore effects that cannot be disregarded. Finally, we conduct a comprehensive parametric study (i.e., fracture toughness, Young's modulus, Poisson's ratio, horizontal stress ratio, and permeability) on wellbore strengthening fracturing.

The proposed model is useful for wellbore strengthening applications using the intentionally induced fractures (i.e., near-wellbore fracturing). Particle size distribution (PSD) of WSM can be designed based on the simulated fracture geometry. No complex model mesh generation or assignment of boundary conditions are needed, which are commonly used in finite element simulation or other numerical methods. The proposed model can also be used to optimize wellbore strengthening operations by performing sensitivity analysis.

1. Introduction

While drilling to a target zone in a new well, one may encounter lost circulation in depleted sections due to oil production from old wells (Majidi et al., 2015). In depleted reservoirs, the reduction of pore pressure may cause land subsidence (Geertsma, 1973; Zhang et al., 2016a; Gao and Gray, 2017) and the reduction of in-situ stresses, which is known as stress path (Addis, 1997; Shahri and Miska, 2013; Rafieepour et al., 2017; Rafieepour and Miska, 2017). According to the tensile fracture criterion, the corresponding fracture pressure decreases (Brudy and Zoback, 1999). As the neighboring formations keep their original fracture gradient, drilling through these weak zones can easily induce fractures and may cause severe lost circulation (Chen et al., 2014, 2015). A field example from an offset well in Caspian Sea is shown in Fig. 1 (Salehi and Nygaard, 2011). A weak zone is located at the section of 17517′-20500’. The drilling mud weight window is very narrow in the weak zone and the pressure profiles of neighboring formations are normal. The lost circulation can be easily induced. Lost circulation of drilling fluids can cost \$2–4 billion per year in the global drilling industry (Growcock, 2010). By applying wellbore strengthening techniques, the fracture gradient can be increased in weak zones and the benefits of less drilling cost and fewer casings can be achieved.

Over the past three decades, different wellbore strengthening techniques and theories have been proposed and successfully applied in

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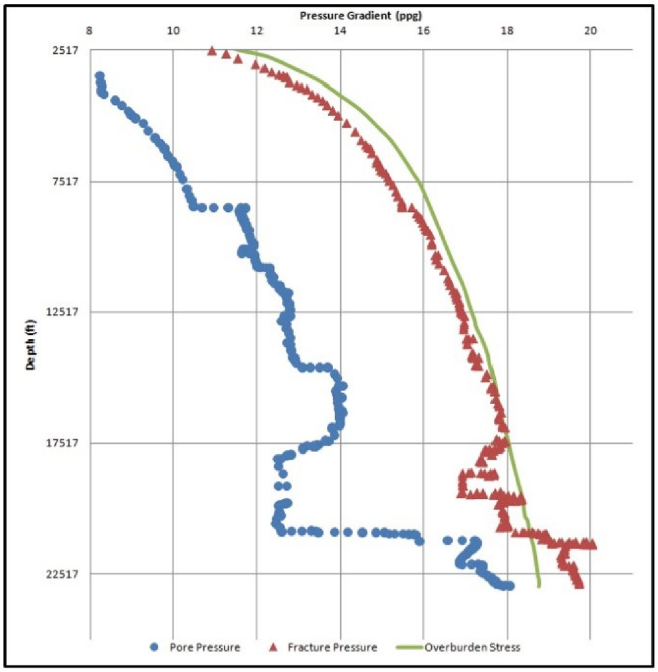

Fig. 1. Drilling mud window with a weak zone (after Salehi and Nygaard, 2011).

the industry. Non-fracture-based techniques include chemical (Aston et al., 2007; Growcock et al., 2009), thermal (Shahri et al., 2015; Wang et al., 2017; Wang and Chen, 2018), and mud plastering methods (Salehi and Kiran, 2016; Feng et al., 2018a, 2018b). Recently, Wang et al., 2017 and Wang and Chen 2018 conducted analysis of thermally induced stresses in the near-wellbore region. High temperature zone around the wellbore can increase the hoop stress. However, cooling effects due to mud invasion on surrounding formation can cause the reduction of hoop stress, which leads to a lower fracture reopening pressure in wellbore strengthening. On the other hand, fracture-based techniques mainly include fracture propagation resistance (Fuh et al., 1992; van Oort et al., 2011), stress cage (Alberty and Mclean, 2004), and fracture closure stress (FCS) (Dupriest, 2005). The similarity of these techniques, although they have different theories or procedures, is to plug induced or pre-existing fractures with a blend of WSM in the near-wellbore region. As a result, the pressure acting on the fractures can be reduced due to the isolation of WSM. From the standpoint view of fracture mechanics, the FROP can be increased because it requires higher wellbore pressure to induce fracture propagation. Finally, the wellbore is strengthened due to the increase of fracture gradient. Therefore, it is very important to know the fracture geometry in real-time for induced fractures with respect to the PSD design of WSM.

Studies on wellbore strengthening fracture models can be categorized into numerical methods and analytical/semi-analytical methods. For numerical methods, the finite element method and boundary element method are mainly used. Alberty and Mclean (2004) proposed the stress cage theory and used the finite element model to obtain the hoop stress increase after WSM plugging. The line crack solution was used to estimate the fracture geometry. Salehi and Nygaard (2012) employed a three-dimensional finite element model for investigating wellbore strengthening mechanisms and described a procedure for designing PSD in field applications. Feng et al. (2015) also used the finite element model to obtain the fracture width distribution and conducted a thorough parametric study of wellbore strengthening. Wang et al. (2007, 2009) developed a boundary element model to analyze fracture behavior and investigated the influence of various rock and well conditions on wellbore strengthening. Zhong et al. (2017a) employed a dislocation fracture model to obtain the fracture profile in real-time for wellbore strengthening applications but the wellbore pressure was an input in the model. Recently, Zhao et al. (2017)and Zhao and Gray (2017) developed a coupled hydraulic fracturing model based on the cohesive zone model to investigate the wellbore strengthening phenomenon. For closed-form analytical or semi-analytical solutions of fracture width distribution, different approaches have been used (e.g., rock mechanics, fracture mechanics, empirical correlations, etc.). Deeg and Wang (2004) used a slit-like fracture model to calculate fracture propagation pressure and fracture width distribution. Guo et al. (2011) developed a closed-form solution for fracture mouth width calculation based on the results of finite element simulations. Shahri et al. (2014) employed the dislocation-based fracture model to develop a semi-analytical solution for fracture width distribution. Mehrabian et al. (2015) and Mehrabian and Abousleiman (2017) presented a linear elastic fracture mechanics based model to calculate the extended drilling margin and also considered the case of multiple fractures. Zhang et al. (2016b) extended an analytical line crack solution to obtain the fracture geometry and verified it against the results of finite element simulations. In general, the deficiency of these fracture models was to only consider static fracture cases. On the other hand, many 2D and 3D hydraulic fracture models (Perkins and Kern, 1961; Geertsma and Klerk, 1969; Cleary, 1980; Carter et al., 2000; Zhong et al., 2014) have been developed to capture dynamic fracture behavior for well stimulation treatments. However, the disadvantage of these models was to disregard near-wellbore effects and WSM plugging. Thus, to overcome the deficiencies of previous wellbore strengthening models and hydraulic fracture models, there is a need to develop a fast-running dynamic fracture model that can consider the near-wellbore effects and WSM plugging for wellbore strengthening applications.

In this paper, an integrated fluid flow and fracture mechanics model that characterizes near-wellbore-induced fracture behavior is proposed. Fluid mass conservation is coupled in the model and fluid linear momentum conservation is examined. We justify the assumption that the fluid pressure inside the fractures can be equal to the wellbore pressure during fracture propagation. The dislocation method (Warren, 1982; Carbonell and Detournay, 1995; Shahri et al., 2014) is employed to obtain the pressure-width relationship and the stress intensity factor. The calculated stress intensity factor is compared to the fracture toughness as the fracture propagation criterion. We validate the stress intensity factor and FROP with Tada's model and Feng's model, respectively. The proposed model is then compared with large leak-off solutions of the PKN fracture model. Finally, a comprehensive parametric study on wellbore strengthening fracturing is performed.

2. Mathematical modeling

2.1. Conventional hydraulic fracturing vs. wellbore strengthening fracturing

Accurate prediction of fracture geometry is important for the effective design of WSM. However, conventional hydraulic fracture models may not be appropriate for wellbore strengthening design because they disregard near-wellbore effects. In this section, the differences between conventional hydraulic fracturing and wellbore strengthening fracturing are discussed. Fig. 2a shows a schematic for conventional hydraulic fracturing. The wellbore size is much smaller than the fracture length. The fractures propagate perpendicular to the direction of the minimum horizontal stress (σ_h). Fig. 2b shows a schematic for wellbore strengthening fracturing. The wellbore size has the same magnitude as the fracture length. In general, the ratio of fracture length to wellbore radius is much smaller in wellbore strengthening fracturing.

The major difference between conventional hydraulic fracturing and wellbore strengthening fracturing is the presence of a wellbore. In other words, the modeling of conventional hydraulic fracturing usually disregarded the presence of the drilled borehole. This is not a bad assumption for conventional hydraulic fracturing because the induced