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Critical pressure of closure fracture reopening and propagation: Modeling and applications

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ABSTRACT

The reopening and propagation of natural closure fracture is one of the key causes of lost circulation in the fractured formation, which is directly related to safe and efficient drilling. In this paper, considering dip angle and dip direction of the fracture, the stress state on closed fracture surface near borehole is analyzed. Meanwhile, combining the critical mechanics condition of fracture reopening and propagation, a new model of the critical pressure for reopening and propagation of natural closure fracture is established based on rock mechanics theory and Linear Elastic Fracture Mechanics (LEFM), and the corresponding solution algorithm is proposed. Furthermore, the new model is utilized in investigating reopening and propagation of natural closure fracture, which intersects with the horizontal well along direction of the minimum horizontal principal stress σ_h, for R1 formation of HF oilfield in the Middle East. And the stress distribution on the fracture surface and critical pressure contour is presented. The result indicates that the normal stress and shear stress on the fracture surface near the wellbore are of central symmetry. Moreover, critical pressure distribution of reopening and propagation of closed fracture is symmetrical. The critical reopening pressure of natural closure fracture of R1 formation is consistent with the actual mud loss pressure, therefore the new model is reliable. This work provides a scientific foundation for drilling fluid density design for fractured formation. It can effectively avoid drilling and completion leakage, which eventually prevents drilling problems and dwindles drilling cost, as well as offer a theoretical support for fast, safe and efficient drilling.

1. Introduction

Reopening and propagation of naturally closed fractures are an important cause of well lost circulation while drilling and completion. Since reopening and propagation of natural closure fracture are caused by an exorbitant density of drilling fluid, it will result in different severity leakage while drilling and well completion (Cook et al., 2011; Lu et al., 2012; Majidi et al., 2010). Once the leakage appears, not only the loss of drilling fluid, treatment agent consumption and severe reservoir damage, but also wellbore collapse or well blowout may occur. Worst of all, complicated downhole issues may arise. Hence, it is difficult to guarantee a safe and efficient drilling, and the substantial Non-Productive Time (NPT) and the cost of operation will be increased (Calçada et al., 2015). Globally, due to the problem of leakage, the economic losses approximately are $1 billion per year, which seriously influences the exploration and development of oil and gas resources (Dodson et al., 2004; Shahri et al., 2014; Feng et al., 2015; Feng and Gray, 2016a; Oyedere et al., 2016). Therefore, aiming to the fractured formation, a proper drilling fluid density to prevent natural closure fracture reopening and propagation is really critical to resolve such leakage problems during drilling and completion.

In order to solve the lost circulation problems while drilling and well completion, the current investigations paid more attention to plugging. And the focus of research is shifted from plugging fracture and cave to wellbore strengthening (WBS). The main principle is that Well Strengthening Materials (WSM) and Loss Circulation Materials (LCM) which are mixed with drilling fluid are embedded in the fracture, which can support and bridge the induced or existing fractures to block the leakage channel. Gradually, WBS has become an important means to strengthen the wellbore and widen the safe drilling fluid density window (Fuh et al., 1992; Aston et al., 2004; Wang et al., 2005; van Oort et al., 2011; Ali et al., 2014). Its main theories and methods are as follows:

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①Borehole hoop stress enhancement, including stress cage and Fracture-Closure Stress (FCS) method (Alberty and McLean, 2004; Dupriest, 2005, Dupriest et al., 2008; Shahri et al., 2014; Aston et al., 2007; Guo et al., 2014; Mehrabian et al., 2015; Wang et al., 2009; Feng and Gay, 2016a, b; Ruud, 2016); ②Fracture Propagation Resistance (FPR) (van Oort et al., 2011); ③Tip Screen-out (Morita et al., 1990; Fuh et al., 1992). These strategies still emphasize on treatment of leakage rather than previously preventing the reopening and propagation of closure fracture. For plugging fractures, even if the fractures are temporarily blocked successfully, since the plugging zone needs to withstand surge and swabbing pressure, the leakage passageway will be in an alternating pressure state. If the wellbore pressure exceeds pore pressure, the bridge plugging particles may break through the channel toward the formation. Conversely, if the wellbore pressure is lower than pore pressure, the bridge plugging particles may be spit out into the wellbore again, which easily cause the sealing instability and failure of plugging zone, and then the leakage will happen again (Xu et al., 2014). Therefore, the closed fracture reopening and propagation should be initially prevented to ensure that no leakage channels will be generated in the formation, as well as the leakage treatment after mud loss arises, which is crucially significant to leak proof in the fractured formation while drilling and well completion.

The key to prevent fracture reopening and propagation in the formation is to acquire an accurate critical pressure for fracture reopening and propagation. Currently, majority of researches are conducted using experiments or mathematical models to infer critical pressure for reopening and propagation about closed fractures. As for the experimental study, the artificial core samples are utilized to inject the fluid into the prefabricated fracture, then record normal stress of the fracture opening to deduce the fracture opening pressure (Zhou et al., 2008). Nevertheless, the fracture propagation pressure is usually gained by well site or lab Leak-Off Testing (LOT) or Extended Leak-Off Testing (XLOT) (Onyia, 1994; Morita et al., 1996a, b; Jiang and Wang, 1999; Wang et al., 2008; Zhang and Roegiers, 2010; Kumar et al., 2015; Razavi et al., 2016). The experimental technique can obtain a more accurate data, but the core sample cannot reflect the real internal stratum situation and the experiment is too costly, and plenty of materials and manpower are consumed. With regard to fracture reopening models, taking in account in-situ stresses, borehole size, drilling fluid and other factors affecting fracture opening and propagation, through establishing complex mathematical models or building the finite element model based on linear elasticity, fracture reopening pressure can be obtained (Carbonell and Detournay, 1995; Alberty and McLean, 2004; Guo et al., 2014; Arlanoglu et al., 2014; Feng et al., 2015; Feng and Gray, 2016a, b). For fracture tip propagation, with the wellbore pressure, rock mechanical parameters and in-situ stresses considered, a linear borehole strengthening mathematical model or finite element model for fractured formation are launched. And the law of the stress intensity factor with change of the fracture length and plugging position has been investigated. Nevertheless, there are few researches on the critical pressure of fracture propagation (Wang and Pu, 2010; Yang et al., 2012; Ai et al., 2014; Kang et al., 2014; Feng and Gray, 2016a, b). At present, the most fracture reopening and propagation model assumes that the fracture is a line fracture, where only one dimension is considered. Accordingly, the fracture is not dealt with as a surface and the occurrence of fracture is neglected, which does not meet the actual underground situation. There is no consideration of the stress difference on the fracture surface. And the regularity of fracture mouth reopening and the tip propagation has not been revealed, which is needed to be further improved.

In this paper, with the fracture occurrence (dip direction and dip angle) and fracture surface stress distribution taken into consideration, the subterranean three-dimensional stress state of fracture surface and the criterion of closed fracture mouth reopening and tip propagation are analyzed. Furthermore, a new calculation model of the critical pressure for the closed fracture mouth reopening and tip propagation is set up and the corresponding numerical model calculation method is put forward. This model was applied to predict the fracture reopening and propagation pressure and regularity of fractured formation (R1) for the HF oilfield in Middle East. The mud loss problem was successfully solved and validity of the model is confirmed. Therefore, this study can offer some certain guidance to prevent well leakage in fractured formations.

2. Critical pressure model for closed fracture reopening and propagation

2.1. Mechanism of closed fracture reopening and propagation

For the closed fracture, the interior of it does not contain fluids, to intersect the wellbore, as the wellbore pressure is gradually increased, once the internal fluid pressure of fracture surface is more than the normal stress σ_{NF}, the closed fracture reopens. With the rise of the wellbore pressure, the opening process gradually develops from fracture mouth into the interior of fracture and to tip. For example, fracture mouth on the intersection between the fracture and wellbore, when the pressure reaches a certain P_w, fracture mouth will reopen at point A. At this time, the P_w is called the critical fracture reopening pressure (Fig. 1a). Along with the drilling fluid entering into the fracture, the liquid pressure acts on the fracture surface. If the drilling fluid pressure exceeds the compressive stress of fracture surface point, fracture gradually will reopen at that point. Until the reopening of the fracture exerts to B (one point of fracture tip), then fracture propagation will occur at point B once the fluid pressure exceeds the fracture tip propagation pressure. This wellbore pressure P_w is defined as the critical pressure of the fracture tip propagation (Fig. 1b). Afterwards, the opening process of closed fracture is transformed into the fracture propagation process, and the lost circulation will be further aggravated.

2.2. Critical mechanics condition for closed fracture mouth reopening and tip propagation

2.2.1. Critical mechanics condition for closed fracture reopening

Generally, there exists often some fillings in the fracture. But since the cementation strength of the filling material is much lower than that of the rock matrix, the cementation strength of the internal filler can be neglected. When the drilling fluid pressure P_w exceeds the minimum compressive normal stress $(\sigma_{NF})_{mouth}$ which acts on the point of natural fracture mouth, fracture mouth will reopen (Liu and Ai, 2015; Zhou et al., 2008). The critical mechanics condition of closed fracture mouth reopening can be expressed as Eq. (1).

$$P_w \geq \min(\sigma_{NF})_{mouth} \tag{1}$$

2.2.2. Critical mechanics condition for closed fracture tip propagation

When the formation is drilled through the borehole, if wellbore pressure is higher than the sum of the minimum circumferential stress $\sigma_{\theta\theta}$ around the borehole wall rock and tensile strength S_t, the borehole wall rock will burst at the point of minimum circumferential stress (Howard and Scott, 1951; Morita et al., 1990; Lu et al., 2012). At this time, the fracture pressure P_f can be derived as Eq. (2).

$$P_f \geq \min(\sigma_{\theta\theta}) + S_t \tag{2}$$

Usually, fractures strike of the undisturbed formation develops along direction of maximum principal stress, the required propagation pressure is minimal under this case. When the fluid pressure surpasses the sum of the minimum principal stress σ_h and tensile strength S_t, the fracture will propagate. When the pressure inside the fracture is less than minimum principal stress, the fracture will be closed (Ali et al., 2014; Zeng et al., 2016). In this case, this pressure for fracture propagation P_e can be expressed as Eq. (3).

$$P_e \geq \sigma_h + S_t \tag{3}$$

The Eq. (3) is applicable to the undisturbed formation which is far