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Parametric study of controllable parameters in fracture-based wellbore strengthening

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A B S T R A C T

Fracture-based wellbore strengthening techniques have been widely used in the oil industry to reduce the cost of lost circulation, especially in depleted reservoirs. Accurate prediction of induced-fracture geometry is of critical importance for best particle size distribution (PSD) selection of wellbore strengthening materials (WSM). Conventional parametric analyses mainly focused on rock properties, well conditions and WSM plug location. Thus, the deficiency of ignoring time and fluid dynamics may result in erroneous operations. In this paper, a dynamic fracture model based on the dislocation method is employed to qualitatively characterize the influence of controllable parameters on fracture propagation and fracture reopening pressure (FROP). Fracture propagation length and profile are obtained for each parameter with different values. It is found that fluid injection rate, fluid viscosity, fluid injection time, wellbore inclination and wellbore radius have an inverse relationship with FROP. On the other hand, fracture plug width has a positive relationship with FROP. Finally, a procedure for determining optimal wellbore strengthening operations by manipulating the controllable parameters is developed based on the dynamic fracture model.

1. Introduction

The main objective of wellbore strengthening is to avoid the significant cost and risks caused by lost circulation. The origin of wellbore strengthening is DEA 13 project conducted in the 1980s. It was found that water-based muds have higher fracture propagation pressure than that of oil-based muds (Fuh et al., 1992). Over the years, a number of fracture-based wellbore strengthening techniques have been proposed and successfully applied in the industry (Fuh et al., 1992; Alberty and Mclean, 2004; Dupriest, 2005; van Oort et al., 2011). Some experimental studies and field data have also validated the applicability of these techniques (Aston et al., 2004; Song and Rojas, 2006; Whitfill et al., 2006; Aston et al., 2007; Cook et al., 2011; Guo et al., 2014; Razavi et al., 2015). The main process of fracture-based strengthening techniques is to plug the preexisting or induced near-wellbore fractures by adding a certain WSM mixture to increase the FROP. One of the major problems encountered in this process is inaccurate prediction of induced fracture geometry. Semi-analytical solutions (Guo et al., 2011; Shahri et al., 2014; Mehrabian et al., 2015; Zhang et al., 2016a) and numerical models (Alberty and Mclean, 2004; Wang et al., 2009; Morita and Fuh, 2012; Feng et al., 2015) are available for static fracture geometry prediction.

Numerous studies have been performed to investigate the influencing factors for wellbore strengthening. Wang et al. (2009) employed a boundary element model to investigate the influence of rock properties, fracture pressure and wellbore conditions on fracture width and tangential stress distribution. Morita and Fuh (2012) performed a parametric analysis of wellbore strengthening methods from basic rock mechanics. Various rock properties, fluid pressures and wellbore conditions were studied to obtain the pressure buildup after WSM plugging. Shahri et al. (2014) developed a fast-running, semi-analytical model based on the dislocation method to calculate the fracture width and stress intensity factor. Later, Shahri (2015b) performed a comprehensive parametric analysis of fracture-based and non-fracture-based wellbore strengthening that included thermal and mud cake effects. Feng et al. (2015, 2016a) used finite element modeling and a fracture mechanics-based model to characterize the influence of plug location, wellbore conditions, and rock properties. However, the influence of time and fluid dynamics during fracture propagation were not considered in these studies.

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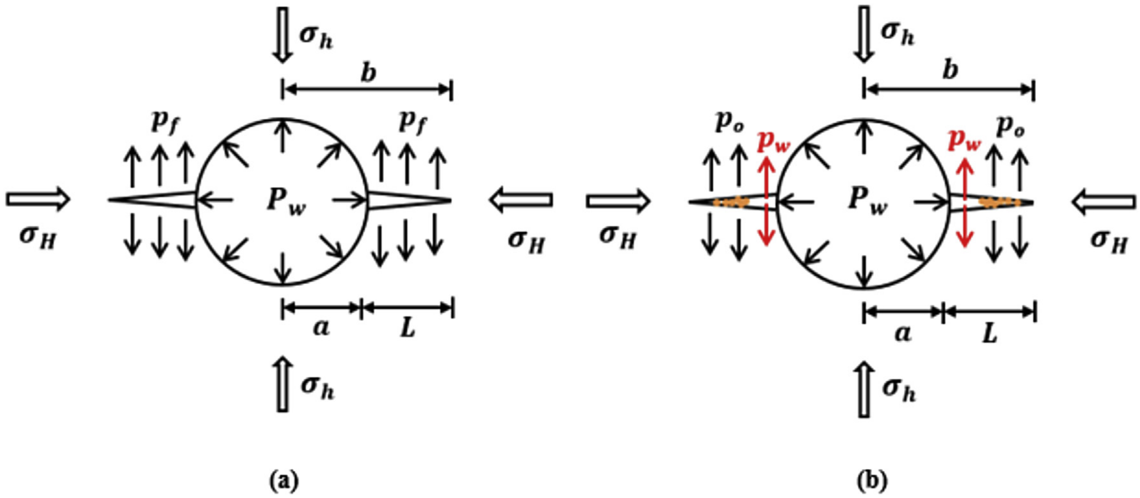

Fig. 1. Schematic of the wellbore strengthening model (a) before WSM plugging. (b) after WSM plugging.

This paper presents a comprehensive parametric study of some controllable parameters among influencing factors on fracture propagation and FROP. The larger difference between FROP after WSM plugging and formation breakdown pressure (FBP) indicates better wellbore strengthening. A dynamic fracture model based on the dislocation method (Warren, 1982; Carbonell and Detournay, 1995; Shahri et al., 2014; Zhong et al., 2017) with fluid mass conservation is employed. To calculate the FROP, wellbore pressure is increased until the stress intensity factor exceeds the fracture toughness. The influencing factors can be summarized into four categories: rock properties, fluid properties, well conditions, and WSM properties. Controllable parameters in these categories are examined for influence on fracture propagation and FROP. Finally, a procedure is developed to obtain optimal wellbore strengthening operations based on the simulation results.

2. Mathematical modeling

Fig. 1a shows the model before WSM plugging. The surrounding medium (rock) is assumed to be homogeneous. Far-field stresses (the maximum horizontal stress σ_H and the minimum horizontal stress σ_h) are applied from infinity. The wellbore pressure is p_w and pressure inside the fracture is p_f, which is assumed to be the same as wellbore pressure. Two symmetric fractures are induced from the wellbore and the propagation direction is perpendicular to the minimum horizontal stress. Fig. 1b shows the fracture model after WSM plugging. The WSM (shown as brown particles) are plugged in the fractures. Due to the isolation of WSM, we assume that the fluid pressure in the plug zone (occupied by WSM) decreases to pore pressure, P_o. On the other hand, the fluid pressure of the unplugged zone in the fractures is still the same as the wellbore pressure because the fluid has direct contact to the wellbore.

The superposition principle, dislocation method, and plane-strain theory are used in the models. An intact wellbore is superposed with a fractured wellbore. To consider the fluid dynamics, the fluid mass conservation equation of a single fracture is written as

$$\frac{\pi}{4}H\int_0^{L(T)} w(x,t)dx + H\int_0^T\int_0^{L(t)} u(x,t)dxdt = \frac{1}{2}\int_0^T q_0(t)dt \quad (1)$$

where H is fracture height and $L(T)$ is fracture length at time T; $w(x, t)$ is fracture width and $u(x, t)$ is fluid leak-off velocity; $q_0(t)$ is fluid injection rate. If the injection rate is constant, Eq. (1) can be written as

$$\frac{\pi}{4}H\int_0^{L(T)} w(x,t)dx + H\int_0^T\int_0^{L(t)} u(x,t)dxdt = \frac{1}{2}Q_0T \quad (2)$$

Where Q_0 is the constant injection rate. The leak-off velocity $u(x,t)$, is a history-dependent parameter that can be characterized by Carter's leak-off model (Howard and Fast, 1957)

$$u(x,t) = \frac{2C_l}{\sqrt{t-\tau(x)}}, \quad t > \tau(x) \quad (3)$$

where C_l is the leak-off coefficient and $\tau(x)$ is the fracture tip arrival time at position x. If the formation fluid controlled and wall-building (mud cake) effects are ignored, the leak-off coefficient is (Craft et al., 1962)

$$C_l = 0.0469\left(\frac{k\Delta p\varnothing}{\mu}\right)^{1/2} \quad (4)$$

where Δp is the differential pressure between the fluid pressure

Table 1
Influencing factors of wellbore strengthening.

	Influencing factors
Rock properties	Young's modulus
	Poisson's ratio
	Porosity
	Permeability
	Tensile strength
Fluid properties	Injection time (controllable)
	Injection rate (controllable)
	Viscosity (controllable)
Well conditions	Wellbore radius (controllable)
	Wellbore inclination (controllable)
	Wellbore azimuth (controllable)
	Pore pressure
	Far-field stresses
WSM properties	PSD (controllable)
	Concentration (controllable)
	Shape (controllable)