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Opening of natural fracture and its effect on leakoff behavior in fractured gas reservoirs

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ABSTRACT

Fluid leakoff is one of the most important issues frequently encountered in hydraulic fracturing, especially in naturally fractured gas reservoirs. Opening of natural fractures will bring about excessive fluid loss and restrain the propagation of major hydraulic fractures. A mathematical model of natural fracture dominant leakoff in fractured gas reservoirs has been developed in this paper. Besides, the opening mechanism of natural fractures has been discussed and a new criterion is proposed. Simulation results indicate that open natural fractures have a dominant effect on fracturing fluid leakoff. The wider the opening of the natural fractures, the larger the leakoff of fracturing fluid. The opening of natural fractures depends not only on stress but also the hydrodynamic size of polymer molecules. Due to the formation of filter-cake, the solid phase in fracturing fluid, consisting of polymer residues, formation fines and fluid loss additives plays an important role in the fluid leakoff behavior, which could be divided into two regions, solid dominant region and reservoir dominant region. Moreover, the leakoff behaviors between slick water and cross-linked fluid are compared for shale gas reservoirs, demonstrating that it is easier for slick water to seep into natural fractures and produce a fracture network.

1. Introduction

Fluid leakoff is a major theoretical and technical concern in hydraulic fracturing. In shale gas reservoirs, large leakoff of slick water creates the fracture network, approximated as the Stimulated Reservoir Volume (Mayerhofer et al., 2010). Leakoff in naturally fractured reservoirs shows a dual-leakoff phenomenon (Warpinski, 1990). Excessive fracturing fluid loss has been widely observed above a threshold pressure and is thought to be caused by the opening of natural fractures. Therefore, it is worthy of determining the criterion for natural fracture opening and the magnitude of fluid loss after natural fracture opens. This paper amis to shed light on these two questions.

The opening of natural fractures mainly depends on stress, as can be predicted by existing correlations (Nolte and Smith, 1981), which agrees well with field observations. Recently, the interaction between the propagation of hydraulic fractures and natural fractures has been widely discussed (Chuprakov et al., 2011; Dahi-Taleghani and Olson, 2011; Gu et al., 2012). Most of these studies tried to describe the processes when a hydraulic fracture crosses a frictional interface (a pre-existing fracture). However, reports about the influence of structure and hydrodynamic size of gel or polymer on the opening of natural fracture are relatively rare.

Pressure interpretation is the most popular means to calculate the magnitude of the fluid leakoff. Many studies (Barree and Mukherjee, 1996; Barree and Conway, 2001; Castillo, 1987; Cuesta and Markland, 1990; Mayerhofer and Economides, 1997; Mayerhofer et al., 1995) have investigated the pressure dependent leakoff and the effect of leakoff on fracture geometry, proppant placement and post-fracturing production. Nevertheless, theoretical models for leakoff volume and rate prediction are scarce. Modeling of flow behaviors when hydraulic fractures intersect with a natural fracture indicates that significant flow disturbances occur around the point of intersection, which could cause unexpected pressure drops during fracturing (Stahl and Clark, 1991). Also, a dual-media model has been built for leakoff simulation in naturally fractured reservoirs (Li et al., 2007). Nonetheless, it treats all natural fractures as open fractures, which essentially provide the same fluid flow capacity.

In this work, to simulate the fluid leakoff in naturally fractured gas reservoirs we developed a new model which contains two parts, fluid flow in a single natural fracture and a new dual-media system. The single fracture model takes the width change of fracture caused by formation of filter-cake into consideration. The new dual-media system includes the influence of natural fracture

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opening on fluid leakoff by incorporating the single fracture model into the traditional dual-media model. Propagation of hydraulic fractures was not probed in this work, due to its complexity. However, simulation results from the model here could provide some useful information about the process.

2. Model development

Fluid loss can be described as the leakage of the fracturing fluid out of the main fractures (Li et al., 2007). Fracturing fluid not only leaks into formation matrix but also high permeability channels, i.e. the natural fractures. High fluid loss rate may occur when hydraulic fractures intersect a natural fracture.

Distribution of natural fractures in reservoirs is random and hard to be predicted. Under certain stress conditions, some of them will be activated and open up. These natural fractures whose width may increase to hundreds of microns are classified as wider natural fractures, providing high-speed flow channels for the fracturing fluid. In extreme cases, the natural fractures may begin to dilate (Warpinski, 1991). On the other hand, those closed natural fractures, classified as narrower ones, also provide relatively high-speed channels compared with matrix. A unit of the whole domain for numerical simulation is shown in Fig. 1.

2.1. Mass conservation

2.1.1. Wider natural fracture

In Fig. 1, wider natural fracture is an independent flow channel, where the continuity equation is

$$-\frac{\partial (ub)}{\partial x} - 2u_L = \frac{\partial b}{\partial t} \tag{1}$$

where b is the width of the wider natural fracture, u is the flow velocity in the wider natural fracture, u_L is the flux from the wider natural fracture to the dual-porosity part.

In order to simplify the problem, fluid flow in the wider natural fracture is assumed to be laminar and the fracturing fluid is treated as Newtonian fluid, thus

$$u = -\frac{b^2}{12\mu}\frac{\partial p}{\partial x} \tag{2}$$

where μ is the viscosity of fracturing fluid, p is fluid pressure in wider natural fracture. Substituting Eq. (2) into Eq. (1) results in

$$\frac{b^3}{12\mu}\frac{\partial^2 p}{\partial x^2} - 2u_L = \frac{\partial b}{\partial t} \tag{3}$$

The boundary and initial conditions are

$$p|_{x=0,t} = p_F$$

$$p|_{x=L,t} = p_r$$

$$p|_{t=0,x} = p_r$$

Where p_F is the pressure in major hydraulic fracture, p_r is reservoir pressure.

2.1.2. Dual-media

For single phase flow through dual-media (Warren and Root, 1963), the mass balance of fracturing fluid in the system is

$$\text{In narrower natural fracture: } \phi_{f0}\left(C_\rho + C_f\right)\frac{\partial p_f}{\partial t} = \frac{k_f}{\mu}\frac{\partial^2 p_f}{\partial x^2} - \alpha\frac{k_m}{\mu}\left(p_f - p_m\right) \tag{4}$$

$$\text{In matrix: } \phi_{m0}\left(C_\rho + C_m\right)\frac{\partial p_m}{\partial t} = \frac{k_m}{\mu}\frac{\partial^2 p_m}{\partial x^2} + \alpha\frac{k_m}{\mu}\left(p_f - p_m\right) \tag{5}$$

Where the subscript f and m represent the narrower natural fracture and matrix respectively, ρ is fracturing fluid density. ϕ_{i0} ($i=f$ or m) is the porosity, k_i ($i=f$ or m) is the permeability, C_i ($i=f, m$ or ρ) is the compressibility, p is pressure, μ is the viscosity of filtrate, α is shape-dependent constant.

The boundary and initial conditions are

$$p_f\Big|_{x=0,t} = p_m|_{x=0,t} = p_F$$

$$p_f\Big|_{x=L,t} = p_m|_{x=L,t} = p_r$$

$$p_f\Big|_{t=0,x} = p_m|_{t=0,x} = p_r$$

2.2. Change of wider natural fracture width

Experiments and field cases have shown that polymer or gel in the fracturing fluid could enter the wider natural fractures and damage their conductivity (Sattler et al., 1991). Generally, the opening of natural fracture is wide enough to accommodate cross-linked gel particles. Therefore, it is reasonable to assume that filter-cake could form on the wider natural fracture faces, causing fracture width reduction. In dual-media system, the assumption that the filter-cake is negligible (Li et al., 2007) is adopted.

According to the classic theory, the leakoff velocity through the fracture face is

$$u_L = \frac{C_w}{\sqrt{t}} \tag{6}$$

where C_w is the leakoff coefficient of filter-cake.

The thickness of filter-cake is proportional to the leakoff volume through the fracture face (Xu et al., 2011), which can be expressed as

$$h_c = 2\alpha_d C_w \sqrt{t} \tag{7}$$

where, α_d is cake deposit constant, defined by (Yi and Peden, 1994)

$$\alpha_d = \frac{C_s}{(1-C_s)}\frac{1}{(1-\phi_c)} \tag{8}$$

Thus, the width variation of wider natural fracture is

$$b(t) = b_0 - 2h_c(t) \tag{9}$$