Journal of Petroleum Science and Engineering 171 (2018) 422–430

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

The distinct element method (DEM) and the extended finite element method (XFEM) application for analysis of interaction between hydraulic and natural fractures

Amir Ghaderi[a], Jaber Taheri-Shakib[b,*], Mohammad Amin Sharif Nik[c]

[a] National Iranian South Oil Company, Ahwaz, Iran
[b] Research Institute of Petroleum Industry, Department of Research and Technology of the Rock and Fluid Reservoirs, Tehran, Iran
[c] Research Institute of Petroleum Industry, Department of Research and Technology of the Reservoir Geomechanics, Tehran, Iran

ARTICLE INFO

Keywords:
Hydraulic fracture
Natural fractures
Production
Debonding
Shear failure
Tensile failure

ABSTRACT

Hydraulic fracturing can be considered one of the most effective stimulation methods for fractured network formation. The interaction between induced and natural fractures greatly affects the success of the treatment. In this paper, the extended finite element method (XFEM) and distinct element method (DEM) have been combined to identify the propagation of hydraulic fractures in a porous medium with naturally fractured blocks. DEM is used to investigate hydraulic fractures in a natural-fracture network and evaluate the production flow rate under different apertures and lengths of hydraulic fracture. XFEM is used to simulate the deformation of the natural-fracture interface during the approaching phase of induced fractures as a no-remeshing tool. The results of DEM reveal that length of hydraulic fracturing has a significantly greater effect on production than aperture. Results from XFEM show that tensile and shear debonding of natural fractures change as a function of angle and distance from an induced fracture.

1. Introduction

Hydraulic fracturing is one of the important treatments in the management of fractured reservoirs (FR). Hydraulic fracturing in fractured reservoirs plays a significant role in determining production rate. The interaction between a propagated induced fracture and adjacent fracture blocks is a determinant factor in the success of a hydraulic-fracturing operation in fractured reservoirs. Hydraulic fractures and the stimulation of fractured formations are greatly affected by the interaction between the Induced fracture and the natural fracture network. The interaction interface between natural and induced fractures is an important factor in the propagation of fractures in rock. The natural fracture direction with respect to the hydraulic fracture must be evaluated before the operation. Crack properties in hydraulic fractures depends on many factors, such as the reservoir's pore pressure, the stress anisotropy ratio and leak-off to other layers. The distinct element method (DEM) can be used to simulate hydraulic fracturing, if pre-existing fractures are represented in the bonded particle model (Jalalifar and Taheri Shakib, 2012; Taheri-Shakib et al., 2015, 2012a). The parameters of the distributed natural-fracture network directly govern the natural-fracture distribution; the permeability anisotropy of fractured rock masses are greatly affected by geometric characteristics, such as the orientation, density, length, spacing and junction of the fractures (Liu, 2005; Taheri-Shakib et al., 2015; Sebastian et al., 2015; Taheri-Shakib et al., 2018). It is essential to increase the rate of oil production as it declines over time due to drops in reservoir pressure drop; sealing of natural fractures in the reservoir is also crucial. Hydraulic-fracture aperture and length play different roles in the interaction with natural fractures in the reservoir (Taheri Shakib et al., 2016a). A number of different scenarios are possible: the induced fracture intersects a group of high-permeable or low-permeable natural fractures or parts of the reservoir that are, or are not, participating in flow or the parts with different pore pressures (Jalalifar and Taheri Shakib, 2012; Taheri-Shakib et al., 2016b). The technology for diagnosing fractures reveals that complex fracture networks play a major role in fractured-reservoir production. The governing mechanisms of interaction between induced and natural fractures play a vital role in the creation of a complex fracture network. The effects of natural fractures on induced fractures have been investigated, with some authors providing numerical solutions for predicting their interaction (Ghaderi et al., 2018); Warpinski and Teufel, 1992; Taheri-Shakib et al., 2012b; Wang, 2015; Chen, 2012). Modeling the interaction between

---

[*] Corresponding author.
E-mail address: Taherishakib@ut.ac.ir (J. Taheri-Shakib).

https://doi.org/10.1016/j.petrol.2018.06.083
Received 3 December 2016; Received in revised form 20 June 2017; Accepted 26 June 2018

hydraulic and natural fractures with DEM is cumbersome due to the necessity to update the mesh topology to match the geometry of the fractures. XFEM greatly facilitates the simulation of a propagating fracture, as no remeshing of the domain is required (Hu et al., 2014).

The present paper aims to use DEM and XFEM to model hydraulic-fracture propagation in a natural-fracture network. We describe the governing equations of DEM and XFEM, and We the propagation of hydraulic fractures in a natural-fracture network with DEM, and describe the interaction between the induced and natural fractures using XFEM.

2. Natural-fracture network design using DEM

The ratio of the mean separation between the surfaces to the root-mean-square of surface height is the most significant parameter affecting fluid flow through a rough fracture. This parameter defines the distance that the surface roughness protrudes into the fluid (Brown, 1987). Fluid flow through fractures under normal stress is controlled by the geometry of the fractures' void space and contact area. The fractures' aperture controls the amount of fluid flowing through the fractures. The flow rate depends on the type of contact (corner-to-edge or corner-to-corner), which is given by:

$$q = -K_c \Delta p \tag{1}$$

where k_c is the contact permeability factor.

Real rock fractures have rough walls; the calculation is based on the cubic law for planar fractures, which assumes that a fracture's surface is smooth (Snow, 1968; Zhang et al., 2002; Louis, 1969; Witherspoon et al., 1980). At the edge-to-edge contact the flow rate q in a fracture length l is given by:

$$q = Kfa^3 \frac{\Delta p}{l} \tag{2}$$

$$\Delta p = p_1 - p_2 \tag{3}$$

$$K = \frac{1}{12\mu} \tag{4}$$

where fa is the fracture aperture, μ is dynamic viscosity and Δp is the hydraulic pressure difference exerted between the domains.

The hydraulic aperture is given by:

$$fa = fa_0 - u \tag{5}$$

where fa_0 is the initial fracture aperture at zero normal effective stress and u_n is the normal displacement of contact, which is related to normal stress and rock properties. At the contact, the stiffness can control the stress displacement:

$$\Delta u_n = -\frac{\sigma_n}{k_n} \ or \ u_1 - u_2 = \frac{\sigma}{k} \tag{6}$$

where u_n is normal displacement, with a positive value denoting an opening, σ_n is normal stress and the subscripts 1 and 2 refer to the domain. We set a maximum value of fa in explicit calculation.

The difference between the matrix permeability in hard, fractured rock and the permeability of the fracture network will be ignored in this study. In fracture networks the flow is single-phase, containing incompressible fluid. Moreover, the amount of fluid flow into a fracture network is equal to that flowing out of the network, Darcy's Law of mass conservation:

$$q = \alpha \frac{K}{\mu} \frac{\Delta P}{L} \tag{7}$$

where K is the permeability of the rock matrix, Δp is the pressure difference between both sides, μ is the fluid viscosity, l is the length between both sides, which shows the distance between both sides of the fracture, and α is equal to 1 if there is no crack, but has a higher value in the presence of a pre-existing fracture. UDEM is Universal Distinct Element Method which have been implemented in UDEC software. UDEC has been widely used to study multi-block systems in mining, hydropower, and civil engineering industries for decades; so, there is no need to validate the mechanical response of problems involving multiple blocks. The commercial code UDEC was developed in the 1980s based on the distinct element method (DEM). UDEM (Universal Distinct Element Method) can model fractures in an explicit way; the use of this concept is sufficient because the element size of fracture modelling must be small. Based on cluster status, the permeability multiplier α is updated in UDEC (Bear et al., 1993). Simulation of flow in fractured rock mass can be found in UDEC technical documentation (Udec, 2004). The geometry of a 2-D fracture is assumed to be planar, and the intersections of fractures are assigned as nodes. In connected fractures, the sum of all the flows is zero at each node.

3. Analysis of length and aperture of the hydraulic fracture

Many investigations have validated the theoretical flow law from the parallel-plate model for fluid flow through fractures. Factors proposed for adjusting theoretical equations with respect to fracture apertures are usually determined based on two-dimensional fractures. The results have shown that the complexity of fracture patterns highly depends on the direction of natural fractures relative to the induced fracture. Hydraulic fractures in a fractured reservoir with low production improves the physical properties of reservoir rock by connecting fracture networks to obtain economic production. Studies have also shown that hydraulic-fracture propagation is governed by fracturing fluid properties, rate of injection and natural fractures. Connections between and the apertures of fractures are the principle parameters affecting the production rate in a fractured reservoir with pre-existing fractures. The orientation of propagation in hydraulic fracturing depends on the principle stress direction, complexity and geometry of a fracture network. The distribution and properties of natural fractures affect the complexity of the fracture network (Hakami and Larsson, 1996; Dehghan et al., 2015; Dong and De Pater, 2001).

The block size is considered to be 20*20 m, and to be 2D in horizontal (x–y). Fig. 1-a shows the direction of the natural fractures around the well with respect to the stress axis (x-y). In our model, only the connected natural fractures are exhibited. To analyze more accurately, a hydraulic fracture with a constant aperture along with different sizes is applied in the reservoir (Fig. 1-b). In our simulation, the hydraulic fracture is considered to have two wings. Other input data is specified in Table 1.

Matrix permeability determines a significant portion of cumulative production; however, the natural fracture network has a strong impact on the productivity index, due to the importance of effective permeability. An important consideration in the optimization of hydraulic fractures in a fractured reservoir is the length of induced fractures that can result in more interconnected natural fractures, in turn improving production. One of the main hydraulic-fracture operation issues is ensuring proper fracture length and orientation to intersect sufficient natural fractures that may exist within a few meters to a hundred meters. It should be noted that fracture length is a function of time and fluid pressure (Yew, 1997):

$$Length = 0.68 \left[\frac{S_m q^3}{(1-\nu)\mu h^4} \right]^{1/5} t^{4/5} \tag{8}$$

where t is advancing time, S_m is the shear modulus of formation, ν is Poisson's ratio of formation and h is the fracture height. As shown in Fig. 1, increasing the fracture length from 2 to 6 leads to almost the same production for different apertures. A fracture propagation length below 6 m has not yet intercepted the natural fractures. Increasing the hydraulic fracture length past the intact region will lead to more natural factures contributing to production. Fig. 2 shows that the fracture length plays a more substantial role, and that production is more