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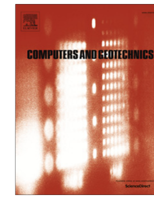

Research Paper

Geometric nature of hydraulic fracture propagation in naturally-fractured reservoirs

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ABSTRACT

The geometry of hydraulic fracture propagation in the absence and presence of natural fractures in reservoirs was studied. The results revealed a marked influence of natural fractures on the symmetry of fracture propagation observed for rock free of natural fractures. Natural fracture properties such as stiffness and approaching angle, and the distance from wellbore to the natural fracture were found to influence the hydraulic fracture geometry. Furthermore, the location of the wellbore with respect to the natural fractures in a reservoir having a system of natural fractures displayed a significant influence on the resulting geometry of hydraulic fracture propagation.

1. Introduction

Use of hydraulic fracturing in unconventional reservoirs such as gas shales and tight gas sandstones has unlocked substantial new resources for commercial natural gas production. Successful hydraulic stimulation is key for the economical production from unconventional reservoirs, which are low porous and low permeable in nature [3]. On another hand, deep geothermal energy has been of great interest as a potential commercial-scale renewable energy source [10,26]. Engineered geothermal systems (EGS) are created mainly using hydraulic fracturing from which a network of interconnected fractures is generated within extremely low-permeable deep geothermal reservoirs for long-term fluid circulation. A comprehensive understanding of the initiation and propagation behaviour of hydraulically-stimulated fractures under reservoir conditions is imperative for successful designs of reservoir stimulations in these applications.

Fluid is injected into the reservoirs through a wellbore during hydraulic fracturing and fractures are initiated from the wall of the wellbore when the applied fluid pressure exceeds the formation breakdown pressure. Eq. (1) expresses the circumferential stress at an arbitrary point away from the wellbore when the wellbore occurs along a principal stress direction [7].

$$\sigma_\theta = \frac{\sigma_H + \sigma_h}{2}\left(1 + \frac{R_w^2}{r^2}\right) - \frac{\sigma_H - \sigma_h}{2}\left(1 + 3\frac{R_w^4}{r^4}\right)\cos 2\theta - P_w\frac{R_w^2}{r^2} \quad (1)$$

where σ_H and σ_h are major and the minor principal stresses, respectively; θ is the fracture initiation angle, i.e., the azimuth of the initial fracture with respect to the direction of the major principal stress; R_w is the radius of the wellbore, and r is the distance from the initial fracture point to the centre of the wellbore and P_w is the internal pressure of the wellbore.

Hydraulic fracture initiates at the point where the tensile circumferential stress is maximum [6,35]. Therefore, when the fracture initiates, $\frac{\partial\sigma_\theta}{\partial\theta} = 0$, which yields,

$$(\sigma_H - \sigma_h)\sin 2\theta = 0 \quad (2)$$

Eq. (2) describes two important scenarios; (1) fracture initiation can have any arbitrary direction (i.e. any value of θ) from the wellbore wall when $\sigma_H = \sigma_h$ and (2) when $\sigma_H > \sigma_h$, double-wing fracture initiation angle, $\theta = 0^\circ$ or $\theta = 180^\circ$, meaning that the fracture propagates parallel to the major principal stress direction.

Geometry of the propagating hydraulic fracture is influenced by parameters such as injection flow rate, viscosity of the fracturing fluid, elastic modulus of the intact rock and injection time. KGD hydraulic fracture model, initially elaborated by Khristianovic and Zheltov [15] and further developed by Geertsma and de Klerk [8], is often used to describe the geometry of hydraulic fractures initiate from a circular wellbore. The KGD model assumes that the hydraulic fractures develop in linear elastic, homogeneous and isotropic medium, fracturing fluid behaves like a purely

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viscous fluid, and the fluid flow in hydraulic fractures is laminar. As Fig. 1 shows, the hydraulic fracture geometry (i.e. length and width) was derived by the KGD model considering a constant height fracture where the fracture width is constant at any horizontal cross section [29]. Fig. 1 further displays that the fracture width is maximum at the wall of the wellbore and it decreases to zero at the fracture tip forming an elliptical shape on a horizontal cross section (i.e. the fracture is at a plane strain condition on the horizontal plane). Note that only one half of the fracture is shown in Fig. 1 and an identical opposite half is assumed. In addition, Geertsma and de Klerk [8] assumed a condition where the opposite faces of the hydraulic fracture close smoothly at the edges such that the normal stress component at the tip of the fracture is finite and equal to the tensile strength of the formation.

According to the closed-form solutions of the KGD fracture model for no leak-off condition stated in Meyer [18], for a hydraulic fracture with unit height, the fracture length (l_t) and aperture width at the wellbore (w_t) can be expressed as shown in Eqs. (3) and (4), respectively.

$$l_t = a\left[\frac{Q^3 G}{(1-\upsilon)\mu}\right]^{\frac{1}{6}} t^{\frac{2}{3}} \tag{3}$$

$$w_t = b\left[\frac{Q^3 (1-\upsilon)\mu}{G}\right]^{\frac{1}{6}} t^{\frac{1}{3}} \tag{4}$$

where Q is the constant injection rate, G is the shear modulus, υ is the Poisson's ratio, μ is the viscosity of the fluid, t is the injection time and a, b are constants.

Both Meyer [18] and Geertsma and Haafkens [9] state that for a hydraulic fracture that propagates along both directions from a wellbore (two-wings fracture) a is 0.48 and b is 1.32, and for a hydraulic fracture that propagates only along one direction from the wellbore (one-wing fracture) a is 0.68 and b is 1.87 (note that the Q used in Eqs. (3) and (4) is the full injection rate applied to the wellbore).

Furthermore, Geertsma and Haafkens [9] presents the expression for wellbore pressure (P_w) variation with hydraulic fracture propagation as shown in Eq. (5).

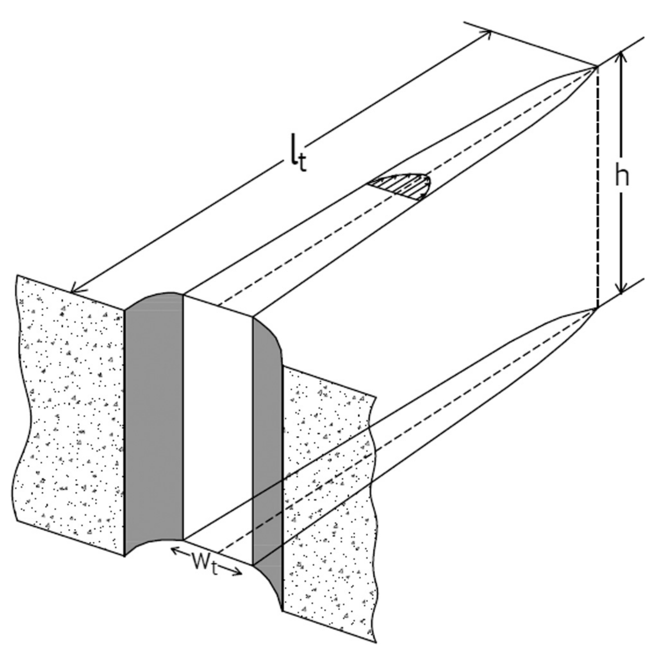

Fig. 1. Hydraulic fracture geometry of KGD constant height fracture model (modified after [29]).

$$P_w = \sigma_{min} + \frac{c}{2}\left[\frac{G^3 Q\mu}{(1-\upsilon)^3 L^2}\right]^{\frac{1}{4}} \tag{5}$$

where σ_{min} is the minor principal stress and c is a constant which is equal to 2.27 for one-wing fracture propagation and 1.91 for two-wings fracture propagation.

It should be noted that the Eqs. (3)–(5) assume that the hydraulic fracture propagates symmetrically about the centre of the wellbore (in case of two-wings fractures) in a medium free of any pre-existing natural fractures (i.e. homogeneous).

Subsurface rocks contain geological discontinuities of different forms such as joints, faults, fissures, and are thus heterogeneous [34,24,25,28]. These discontinuities are referred herein as natural fractures. The presence of these natural fractures can significantly influence the geometric nature of the hydraulic fracture propagation and thus the fertility of the overall stimulation treatment. If the wellbore does not intersect pre-existing natural fractures, hydraulically-stimulated fractures initiated from the wellbore wall can propagate some distance and intersect these natural interfaces [13]. Previous studies report three possible outcomes of the interaction of hydraulically-stimulated fractures with natural fractures; (1) hydraulic fracture crosses the natural fracture with no activation of the natural fracture – crossing, (2) hydraulic fracture opens the natural fracture and the fluid flow diverts into it – opening, and (3) hydraulic fracture propagation discontinues at the intersection with possible shear displacement along the natural fracture – arrest [23]. The objective of the fracturing treatment determines which interaction mode is beneficial over others. For example, a gas production from an unconventional reservoir desires as many fractures as possible created in the resource-bearing rock mass during hydraulic fracturing [21] and thus activation of large natural fractures may not be economically and environmentally benign. The interaction behaviour of hydraulic fractures with natural fractures at their intersection (i.e. crossing vs. opening vs. arrest) is influenced by the reservoir properties, such as hydro-thermo-mechanical properties of the reservoir rock and fractures, in-situ stress state, orientation of the natural fracture with respect to the hydraulic fracture propagation direction (approaching angle), and operational conditions such as fracturing fluid viscosity and injection pressure. Number of experimental (e.g. [4,2,22,36,20]), numerical (e.g. [33,32,14,30,5,27,31,23]) and analytical (e.g. [11,19,31]) studies have been carried out in the literature to understand the influence of reservoir properties and operational conditions on the interaction behaviour of hydraulically-stimulated and natural fractures.

Above review of the literature reveals that the (1) fracture initiation behaviour from a wellbore in a homogeneous medium and (2) interaction behaviour of a propagating fracture with pre-existing natural fractures (i.e. after the hydraulic fracture reaches the intersection point), have been reasonably well documented. However, in case of a heterogeneous system, the geometric nature of the hydraulic fracture propagation between the wall of a wellbore and the potential intersection point on a natural fracture can be influenced by the presence of natural fractures and this has not been thoroughly understood in the literature. We hypothesize that the symmetry of the hydraulic fracture propagation about the wellbore applicable for homogeneous and isotropic systems (as assumed in the KGD fracture model) can be disturbed by the presence of natural fractures in a reservoir. Therefore, in the present study we use distinct element method numerical simulations to qualitatively investigate the effect of the presence and properties of natural fractures on the geometry of hydraulic fracture propagation.