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Conductivity and performance of hydraulic fractures partially filled with compressible proppant packs

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ABSTRACT

Hydraulic or fluid-driven fracturing techniques are often utilised to enhance the production of oil or gas from hydrocarbon reservoirs. There are a number of engineering guidelines to identify the optimum fracture dimensions (i.e. length and average opening) and optimum fracture conductivity, which maximize the efficiency of a given hydraulic fracturing procedure. However, the fracture dimensions as well as conductivity during the production stage may be below the expected design values due to the compressive in-situ stresses, the non-uniform distribution of the proppant within the fracture, as well as the compressibility of the fractured rock and proppant pack.

In this paper, the performance of the hydraulic fracture, which is partially filled with a compressible proppant pack, is evaluated using a simple mathematical model. The mathematical model incorporates the aforementioned effects of proppant compressibility and in-situ stresses. A case study is conducted to investigate phenomena such as: the residual opening of fracture faces not supported by the proppant pack, the compaction of the proppant pack under the action of the confining stresses and the subsequent reduction in the permeability of the proppant pack.

1. Introduction

Hydraulic fracturing is a well stimulation technology used in the oil and gas industry for enhancing hydrocarbon recovery and alleviating near wellbore damage [1]. This technique consists of initiating, propagating and opening a fracture from the wellbore towards a hydrocarbon-bearing layer by a pressurised fluid. Granular particles called "proppants", which range from natural sands to synthetic materials, are pumped into the created fracture along with the fracturing fluid. Once the injection pressure is relieved, they hold open, or "prop" the fracture and prevent its closure due to the in-situ compressive stresses. The proppant filled fracture provides a narrow but very conductive flow path towards the wellbore, increasing significantly the conductivity and production rate of the reservoir.

Several models have been developed in the past for estimating the conditions for fracture initiation and growth in rocks [1–6]. These models are used to predict the geometry of the hydraulic fracture for particular fracturing treatment conditions or to identify fracturing conditions which lead to an optimum fracture geometry. However, the increment in well productivity due to the hydraulic fracture ultimately depends upon the performance of the proppant pack, which controls the length, opening and conductivity of a fracture during the production stage [7,8]. During the proppant injection stage, the sedimentation and screen out of proppant particles may prevent the transport of proppant particles along the entire length of the fracture. As a result, the propped or effective length of the fracture can be much smaller than the length of the fracture initially created during the fluid injection stage [9–11]. During the production stage, the width of the propped fracture also diminishes due to the compaction of the proppant pack and the embedment of proppant particles into the fracture surface [12]. The conductivity of the proppant pack during the production stage may also decline by a few orders of magnitude, compared to the conductivity measured under laboratory conditions, due to several physical and chemical mechanisms [12]. By incorporating the effects of these phenomena, a more realistic estimate of the production rate from the fractured well can be obtained.

The authors have recently considered the some of these effects separately. For e.g. the problem of a fracture partially filled with an incompressible proppant pack has been considered in [13,14] and the effects of proppant pack compaction on the opening and conductivity of the fractures have been considered in [15–18]. In the present work, a more general problem of a fracture partially filled with a loose granular assembly of proppant particles is considered. The fracture is

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subjected to confining stresses, which result in the closure of the unpropped fracture segments as well as rearrangement of proppant particles in the pack, leading to a reduction in fracture opening and conductivity. In the next section, the mathematical formulation of the problem and the modelling assumption are described. Selected case studies and numerical results are presented which demonstrate the effect of the in-situ confining stresses, propped length and proppant pack compressibility on the performance of hydraulic fractures.

2. Problem formulation and modelling assumptions

Consider an isotropic, homogenous, linearly elastic rock formation with Young's modulus E and Poisson's ratio ν. It is penetrated by a vertical hydraulic fracture of length $2l_f$ and height $2h_f$. For the co-ordinate system shown in Fig. 1, the reservoir lies along the x–y plane, the wellbore lies perpendicular to the reservoir along the z-axis and the fracture is located along the x–z plane. The problem geometry is symmetric about the x and y axes.

The problem is formulated in 2D, as illustrated in Fig. 2, i.e. all parameters remain constant along the z-axis. In this 2D formulation, the fracture geometry is described by the Khristianovic–Geertsma–de Klerk (KGD) model [19,20] and the initial opening profile of the fracture, $\delta_0(x)$, is given in accordance with the linear elastic fracture mechanics, by

$$\delta_0(x) = \frac{4}{\overline{E}}\left(\sigma^\infty + p_f\right)\sqrt{l_{f0}^2 - x^2}, \quad (1)$$

where $\overline{E}$ is the reduced Young's modulus defined as $\overline{E} = E/(1-\nu^2)$ for plane strain conditions, σ^∞ is the remote stress normal to the fracture and p_f is the fluid pressure within the fracture during the fracturing treatment. The stresses are assumed to be positive in tension and negative in compression. Since the KGD fracture geometry is based on the plane strain assumption, it implies that the opening or width of the fracture is independent of fracture height [3]. More sophisticated models describing the fracture

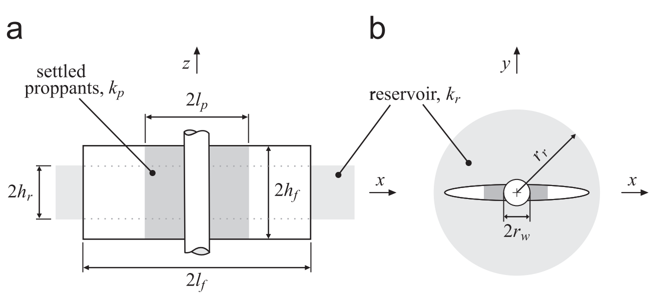

Fig. 1. Schematic diagram of a partially propped hydraulic fracture considered in the problem formulation (figure not to scale), (a) cross-sectional view and (b) plan view.

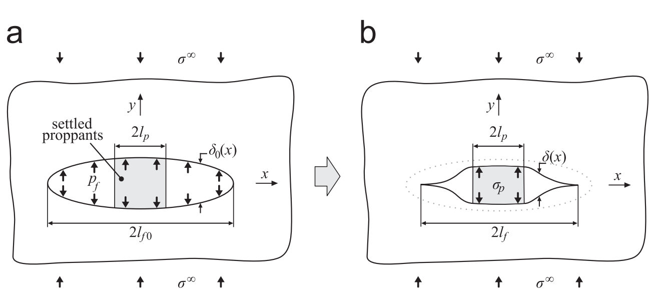

Fig. 2. The 2D approximated of a hydraulic fracture partially filled with proppant and subject to remote confining stress. (a) The initial opening and length of the fracture due to a uniform internal pressure p_f, (b) the residual opening and length of the fracture once the stimulating fluid pressure is removed.

geometry are available in the literature [2–6], however, the plane strain 2D model is more suitable for analytical studies, such as the present one [15,21]. The results based on the KGD model can be reasonably extended to other fracture geometries in the case of short fractures or in the near tip region, which can be modelled locally as a plane strain geometry [22]. Eq. (1) also assumes uniform fluid pressure in the fracture during the fracturing stage, which is the case when the fracture propagates in the toughness dominated regime and there is no significant fluid leak off into the reservoir [21,23].

The fracture is filled with a proppant pack of permeability k_p and porosity η, up to a length $2l_p \le 2l_f$. The proppant pack is assumed to be a granular assembly made up of proppant particles and the deformation of the proppant pack is linked largely to the rearrangement and densification of the loosely arranged particle assembly and the subsequent changes in pore volume. The deformation of the proppant pack is modelled by Terzaghi's soil consolidation model [23,24]. This model is chosen due to its simplicity, since only one parameter governs the deformation vs. stress behaviour or the overall compressibility of the proppant pack. More sophisticated compaction models can be used at the expense of additional empirical parameters or coefficients [25].

The compaction of the proppant pack and the subsequent reduction the porous space between the particles also lead to a reduction in permeability of the proppant pack. This dependence of the permeability on the porosity of the proppant pack is modelled using the empirical Kozeny–Carman equation [26]. It should be noted that the rearrangement of the proppant particles is only one of many mechanisms which lead to the reduction in permeability of the proppant pack during the production stage. Other mechanisms such as crushing and diagenesis of proppant particles and deposition of fines in the pore space [27–29], can also be incorporated into the empirical relationship between permeability and porosity.

During the production stage, it is assumed that the flow within the pore space of the proppant pack as well as the reservoir rock (i.e. at the micro-scale) occurs at small Reynolds number ($N_{Re} < 1$) and can be described by the linearized form of Navier–Stokes equation [28]. Hence, the flow in the reservoir and the flow within the fracture are described by Darcy's law on the macro-scale. Conditions under which the macroscopic flow cannot be adequately described by Darcy's law as well as models which provide a better correlation between pressure drop and flow rate under these conditions, have been reviewed elsewhere [28,34,40]. Poro-elastic effects have also been excluded, which implies that the fluid flow in the reservoir is not coupled with the state of stress in the reservoir.

The aperture and length of the hydraulic fracture at the production stage are defined as the residual fracture opening, $2\delta(x)$ and length, $2l_f$, respectively. The residual opening and length of the fracture depend on the distribution and compressibility of the proppant pack, confining stresses, elastic properties of the reservoir, and on the initial fracture geometry. These are unknown and need to be determined as a solution to a mixed boundary value problem. The solution method that is developed and presented in the next section is based on the distributed dislocation technique, which is a quite standard tool in fracture mechanics modelling [30].

3. Residual opening and length of the hydraulic fracture

The solution for the residual opening and length of the hydraulic fracture can be obtained from the following boundary value problem:

$$\sigma_{yy}(x,y) = \sigma^\infty, \quad x^2 + y^2 \to \infty; \quad (2a)$$

$$\sigma_{yy}(x,0) = \sigma_p(x), \quad |x| < l_p; \quad (2b)$$