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Impact of fluid compressibility for plane strain hydraulic fractures

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ABSTRACT

Growing interest in hydraulic fracturing (HF) using super-critical CO_2 (SC-CO_2) calls into question the typical HF modeling assumption whereby the fluid compressibility is neglected. This paper models a plane strain HF driven by compressible fracturing fluid including the influence of viscous fluid flow, crack propagation through the host rock, and fluid leakoff into the host rock. The results show that, contrary to a reasonable initial hypothesis that compressibility would be important, in expected real world conditions the fluid compressibility has little impact on fracture propagation.

1. Introduction

Hydraulic fracturing technology was developed during the last half of the 1940s and rapidly became one of the most important technologies for oil and gas well stimulation [10,21]. The importance has further increased in the past two decades due to its enabling of the dramatic growth in development of unconventional (very low permeability) reservoirs. Over its 70 year history, many approaches have been taken to model hydraulic fracture growth. But, motivated by a recent rise of interest in super-critical CO_2 (SC-CO_2) fracturing, the assumption of zero compressibility must be revisited. For this, we draw inspiration from past investigations, including Nilson [22,24] who first focused the one-dimensional compressible gas flowing and fracturing problem in which the gas was treated as an ideal gas and the ideal gas law was adopted to describe the gas state. Friehauf and Sharma [11] and Ribeiro and Sharma [26] considered the temperature and pressure influence and proposed a 2D and 3D model, respectively, for hydraulic fracturing with energized fluids. Other authors consider compressibility only in the injection system [1,17,20].

While there exist simulators that include compressibility, and while the impact of compressibility in the injection system is clear, it remains unclear how strong is the impact of compressibility on the system when considered via the fluid mass balance (continuity) equation. Our recent work [29] has shown that the impact on toughness dominated hydraulic fractures (internal pressure is approximately uniform) is small, around 10% at most, in the storage regime and completely negligible in the leakoff dominated regime, with similar results arising for both plane strain and penny-shaped hydraulic fractures. However, it remains to clarify the importance of compressibility for hydraulic fractures wherein viscous flow is not negligible. Thus motivated, this Note presents development of a numerical solution for plane strain hydraulic fracture propagation driven by a viscous, compressible fluid in a permeable rock.

2. Model

The model considers a straight, plane strain hydraulic fracture (HF) characterized by the fracture half-length, $l(t)$, and aperture, $w(x,t)$, where x is the spatial coordinate (Fig. 1). The compressible fluid is injected at a constant rate, Q_0, to drive the fracture through a permeable rock. The pressure inside the fracture, $p_f(x,t)$, is the sum of the net pressure, $p(x,t)$, associated with driving HF growth and the minimum in-situ stress, σ_0. The fluid flux inside the fracture is expressed by $q = uw$, where u is the mean fluid velocity across the fracture width, w.

State equation. With a view of fracturing fluid compressibility, we assume the compressible fluid follows a linear relationship between density and net pressure. By this means, the compressibility is taken into account by

$$\rho = Cp + \rho_0 \quad (1)$$

where C represents compressibility and ρ_0 is the density when fluid pressure is equivalent to the minimum horizontal in-situ stress. Such an assumption of local linearity is valid for typically-expected reservoir temperature-pressure conditions and for net pressure that does not vary too widely compared to a pressure datum that can be taken as the minimum in situ stress σ_0. Such local linearity is illustrated in Fig. 2

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Nomenclature

l	hydraulic fracture length
p	fluid net pressure
p_f	fluid pressure
q	fluid flux (per unit fracture height)
t	time
t^*	characteristic time scale associated with the storage-leakoff transition
$t_0(x)$	the time when the fluid front reaches x
Δt	time step
u	mean fluid velocity
w	hydraulic fracture opening
w_k	tip asymptotic for toughness regime propagation
w_m	tip asymptotic for viscosity storage regime propagation
$w_{\tilde{m}}$	tip asymptotic for viscosity leakoff regime propagation
x	spatial coordinate in longitudinal direction
C	fluid compressibility
C_L	leakoff coefficient ($C' = 2C_L$)
D_n	normal displacement
D_s	shear displacement
E	Young's modulus of the rock
E'	plane strain elastic modulus of the rock
G_{nn}	normal stress influence coefficient caused by normal displacement
G_{ns}	normal stress influence coefficient caused by shear displacement
G_{sn}	shear stress influence coefficient caused by normal displacement
G_{ss}	shear stress influence coefficient caused by shear displacement
K_I	stress intensity factor (mode I)
K_{Ic}	fracture toughness of the rock (mode I, $K' = 4\sqrt{2/\pi}K_{Ic}$)
Q_0	fluid flow from pump into the wellbore
V	fracture propagation velocity
β_m	coefficient used in tip asymptotic for viscosity storage regime propagation
$\beta_{\tilde{m}}$	coefficient used in tip asymptotic for viscosity leakoff regime propagation
γ	dimensionless length of fracture
$\mathscr{K}$	dimensionless toughness
λ	viscous shear stress
μ	fluid viscosity ($\mu' = 12\mu$)
ν	Poisson's ratio of the rock
ρ	fluid density
ρ_0	fluid density when pressure equals minimum in-situ stress
σ_0	minimum horizontal in-situ stress
τ	dimensionless time

based on the pressure-density curves obtained by Span and Wagner [28]. Hence, the compressibility C is the slope of state curve in Fig. 2. Moreover, in experimental conditions, even though the pressure and temperature are lower than under reservoir conditions, the pressure and temperature of SC-CO_2 are still larger than 7.38 MPa and 304.1 K (Super-critical condition of CO_2). Therefore, in Fig. 2, the largest C ranges from 143 to 175 kg/(m^3 MPa).

Continuity equation. The mass pumped into the fracture must be conserved; therefore a mass balance equation for a plane strain fracture driven by a compressible fluid is given by

$$\frac{\partial \rho w}{\partial t} + \frac{\partial \rho q}{\partial x} + \frac{2C_L}{\sqrt{t-t_0(x)}}\rho = 0 \tag{2}$$

Here the first term is a local storage term associated with change in HF width, the second term is the divergence of the mass flux, and the third term represents leakoff according to Carter [4]. This approach treats the leakage of fracturing fluid into the surrounding rock as a one-dimensional diffusion process under the assumptions that the HF propagation velocity far exceeds the characteristic diffusion velocity and that the net pressure is much smaller than the minimum in situ stress. In this manner, Carter leakoff gives the fluid loss rate in terms of $t_0(x)$, which is the time when the fluid front reaches x, and a lumped fluid loss coefficient, C_L, which can include impacts of rock permeability, fluid viscosity, filter cake building, and so forth. Upon substitution of the compressibility law from Eq. (1), the mass balance equation becomes

$$\frac{\partial (Cp+\rho_0)w}{\partial t} + \frac{\partial (Cp+\rho_0)q}{\partial x} + \frac{2C_L}{\sqrt{t-t_0(x)}}(Cp+\rho_0) = 0 \tag{3}$$

Fluid flow equation. The compressible one dimensional fluid flow within the fracture is expressed as [22,23]

$$\frac{\partial \rho w u}{\partial t} + \frac{\partial}{\partial x}(\rho w u^2) + \rho w\left(\frac{1}{\rho}\frac{\partial p}{\partial x} + \lambda\right) = 0 \tag{4}$$

where u is the mean fluid longitudinal (x) velocity and λ is the viscous shear stress. In this paper, only the laminar regime is considered wherein Reynolds number satisfies the laminar flow condition, $Re < 2000$, with a suitable characteristic value computed from $Re = \rho u w/\mu$ [24,32]. For laminar flow, $\lambda = 12\mu u/\rho w^2$, and recall that

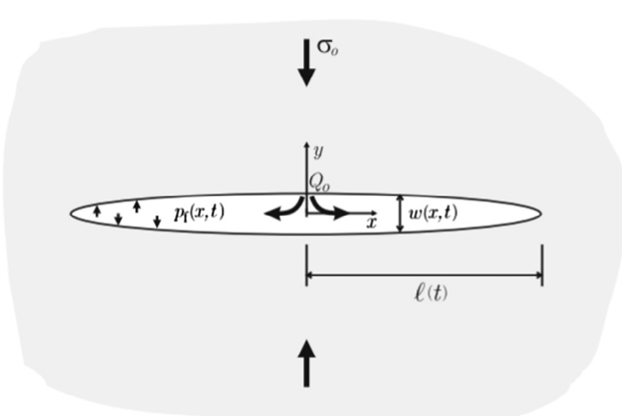

Fig. 1. Geometry of the KGD (plane strain) hydraulic fracture (after Bunger et al. [3]).

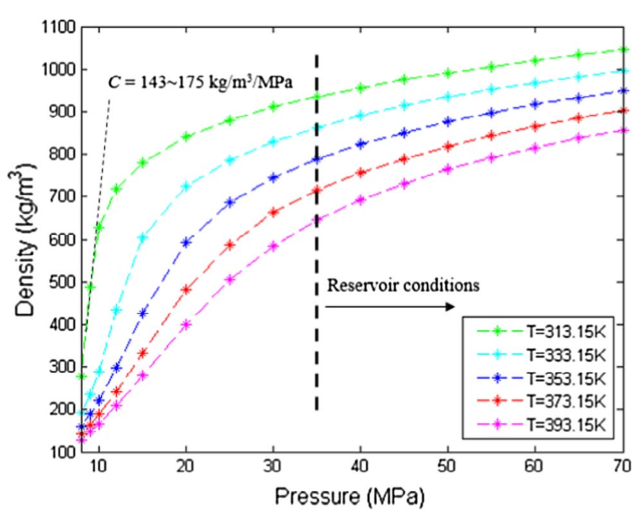

Fig. 2. The relationship between SC-CO_2 density and pressure (after Span and Wagner [28]).