Journal of Petroleum Science and Engineering xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

On subsurface fracture opening and closure

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ARTICLE INFO

Keywords:
Fracture opening and closure
Stress-activated mineral dissolution
Channeling
Radioactive waste disposal
Oil/gas production
In-situ stress indicator

ABSTRACT

Understanding of subsurface fracture opening and closure is of great importance to oil/gas production, geothermal energy extraction, radioactive waste disposal, and carbon sequestration and storage. Fracture opening and closure involve a complex set of thermal, hydrologic, mechanical and chemical (THMC) processes. In this paper, a fully coupled THMC model for fracture opening and closure is formulated by explicitly accounting for the stress concentration on aperture surface, stress-activated mineral dissolution, pressure solution at contacting asperities, and channel flow dynamics. A model analysis, together with reported laboratory observations, shows that a tangential surface stress created by a far-field compressive normal stress may play an important role in controlling fracture aperture evolution in a stressed geologic medium, a mechanism that has not been considered in any existing models. Based on the model analysis, a necessary condition for aperture opening has been derived. The model provides a reasonable explanation for many salient features of fracture evolution in laboratory experiments, including a spontaneous switch from a permeability reduction to a permeability increase in a static limestone experiment. The work may also help develop a new method for estimating in-situ stress in a reservoir.

1. Introduction

Understanding of fracture opening and closure in geologic media is crucial for oil/gas production, geothermal energy extraction, radioactive waste disposal, and carbon sequestration and storage (e.g., Yasuhara et al., 2006; Ellis et al., 2013). It has been observed that, under certain circumstances, a fracture can undergo either opening or closure or switch from one regime to another (Polak et al., 2004; Liu et al., 2006; McGuire et al., 2013). Fracture evolution involves a complex set of coupled physical and chemical processes, including stress-mediated mineral dissolution/precipitation, fluid flow and transport, mechanical deformation, etc. Significant effort has been made to understand these processes in laboratories. For example, in a flow-through experiment on a natural novaculite fracture under moderate effective stress (~14 bars), Yasuhara et al. (2006) observed a reduction in fracture permeability for the first 1500 h followed by a significant increase in fracture aperture as the fluid flow rate and the temperature in the experiment were ramped up. In a similar experiment on a limestone fracture, Polak et al. (2004) observed that, during the initial circulation of groundwater, the differential pressure increased about threefold as the contacting asperities across the fracture were removed. Interestingly, after switching to distilled water, they first observed another threefold reduction in permeability and then a spontaneous switch from a permeability reduction to a permeability increase without any change in experimental conditions. The underlying mechanism for this switch is unknown. An increase in permeability usually involves preferential dissolution channeling (Elkhoury et al., 2013).

Various models have been developed for fracture opening and closure, with various levels of complexity with respect to process couplings, ranging from a simple geometrical model to a coupled thermal-hydrologic-mechanical-chemical (THMC) model (Table 1). However, those models are to a large extent empirical and thus not amenable for predictions. No existing model is able to provide a consistent explanation for some key features of fracture evolution often observed in laboratory experiments, for example, a spontaneous transition from a permeability reduction to a permeability increase (Polak et al., 2004), an enhancement of fracture permeability by temperature (Yasuhara et al., 2006), or a similar enhancement by a low-pH solution (McGuire et al., 2013). Questions, such as what role a normal stress would play in fracture evolution and under what conditions a fracture would tend to open or close, still remain open.

The objective of this paper is to lay a theoretical foundation for modeling subsurface fracture opening and closure. The model proposed below is a fully coupled THMC model that explicitly accounts for three key processes: (1) stress concentration around individual aperture channels, (2) stress-activated mineral dissolution on fracture surfaces, and (3) reactive infiltration instability of fluid flow in fracture aperture. This model is based on a recent observation in materials science that a tangential surface stress may enhance or inhibit mineral reaction on a stressed solid surface (Aziz et al., 1991; Yu and Suo,

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http://dx.doi.org/10.1016/j.petrol.2016.10.051
Received 29 February 2016; Received in revised form 24 August 2016; Accepted 27 October 2016

Please cite this article as: Wang, Y., Journal of Petroleum Science and Engineering (2016), http://dx.doi.org/10.1016/j.petrol.2016.10.051

Table 1
Survey of models for fracture opening and closure. H – hydrologic model; M – mechanical model; HC- hydrologic-chemical model; HM – hydrologic-chemical model; MC – mechanical-chemical model; HMC - hydrologic-mechanical-chemical model; THMC – thermal-hydrologic-mechanical-chemical model.

Type	Model	Processes considered	Note
H	Xie et al. (2015)	Aperture variations due to shear displacement; Navier-Stokes flow in fracture	Purely geometrical for aperture calculations; no mechanics and chemistry considered.
M	Liu et al. (2013)	Two-part Hooke's deformation of fracture aperture	Providing an interesting connection between fracture hydrologic properties (e.g., capillary pressure and relative permeability) and the confining normal stress.
HC	Liu et al. (2005)	Dissolution-induced preferential flow; Advective flow in fracture (cubic law);	No mechanical processes considered.
	Szymczak and Ladd (2009, 2012)	Mineral dissolution; Advective flow in fracture (cubic law); Reactive-infiltration in stability	Detailed analysis on reactive- infiltration instability in a fracture; no consideration of mechanical processes.
HM	Zhao et. (2014)	Pressure solution at contacting asperities; Advective flow in fracture (cubic law); Matrix diffusion in porous fracture walls; Empirical contact area ratio vs. aperture	No consideration of fluid chemistry and mineral dissolution on fracture aperture surface.
	Souley et al. (2015)	Linear elasticity in rock matrix; Nonlinear normal behavior of fracture; Elastic and perfectly plastic behavior of fracture in shear direction; Advective flow in fracture (cubic law)	Purely mechanical and hydrological; no chemistry considered.
	Memoto et al. (2009)	Experimentally determined aperture distribution; Advective flow in fracture (cubic law)	Emergence of directional heterogeneity in fracture aperture due to a shear displacement.
	Min et al. (2004)	Nonlinear normal deformation (empirical); Shear dilation of fracture (empirical); Advective flow in fracture (cubic law)	Focus on discrete fracture networks; no chemical process considered.
	Pyrak-Nolte and Morris (2000)	Fracture stiffness; Fracture aperture deformation; Fluid flow in fracture	Providing a possible connection of fracture flow to fracture aperture and contacting area through fracture stiffness, which can be measured in a field through a geophysical method.
MC	Beeler and Hickman (2004)	Pressure solution of prop; Crack stiffness; Water saturation degree w/r prop material; Effect of curvature on prop solubility	Applicable only to fracture closure induced by prop dissolutions.
HMC	Liu et al. (2006)	Pressure solution at contacting asperities; Free surface dissolution in fracture voids; Channel flow	Providing a geometrical relationship between aperture and asperity dissolution. Not able to explain a spontaneous switch from fracture closure to opening.
	Neretnieks (2014)	Pressure dissolution at contacting asperities Mineral dissolution/ precipitation on fracture void surfaces; Matrix diffusion and mineral precipitation	Showing that matrix diffusion might be important for fracture closure.
THMC	Ghassemi and Kumar (2007)	Fracture aperture change due to thermoelasticity; Advective flow in fracture (cubic law); Heat transport in the fracture; Solute transport; Aperture change to due to mineral dissolution	No consideration of the effect of confining stress on fracture closure.
	Yasuhara and Elsworth (2004, 2006, 2008); Yasuhara et al. (2011)	Temperature-dependent mineral dissolution and chemical diffusion; Pressure solution at contacting asperities; Stress corrosion at contacting asperities; Free surface dissolution in fracture voids; Empirical contact area ratio vs. aperture; Advective flow in fracture (cubic law)	No consideration of the possible effect of surface stress on mineral dissolution on fracture void surface.

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2000). The work presented here will for the first time demonstrate that this mechanism may also play an important role in fracture aperture evolution in a stressed geologic medium. Based on a model analysis, a necessary condition for aperture opening will be derived. The proposed model will be able to explain key features of fracture evolution often observed in laboratory experiments. The geologic implications of the model results will also be discussed.

2. Model formulation

2.1. Geometric representation of a single fracture

It is assumed that a fracture plane can be represented with stripes of contacting areas (asperities) surrounded by aperture channels (Fig. 1). It is further assumed that the cross section of an individual aperture channel can be described by a truncated ellipse defined by the intersection of two identical ellipses (Fig. 2):

$$\frac{x'^2}{a'^2}+\frac{(y'-h)^2}{b'^2}=1 \tag{1}$$

$$\frac{x'^2}{a'^2}+\frac{(y'+h)^2}{b'^2}=1 \tag{2}$$

where x' and y' are the local coordinates; and a' and b' are the major and minor semi-axes of the two intersecting ellipses respectively. Parameters a' and b' are related to the semi-axes of the truncated ellipse (a, b) by (Fig. 2):