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Coupled thermo-poroelastic analysis of drilling induced mechanical damage in fractured rocks

Mostafa Gomar [a], Iraj Goodarznia [a,*], Seyed Reza Shadizadeh [b]

[a] Chemical and Petroleum Engineering Department, Sharif University of Technology, Tehran, Iran
[b] Abadan Petroleum Engineering Department, Petroleum University of Technology, Abadan, Iran

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ABSTRACT

The wellbore represents one of the most crucial components in the hydrocarbon and geothermal reservoir system, as it is the sole conduit to the reservoir for fluid production or injection. Therefore, predicting and controlling of the permeability variations close to the wellbore has been one of the most challenging issues in geothermal and petroleum reservoir systems. A new method is presented to model fracture permeability changes during drilling in fractured rocks. The approach includes finite element method (FEM) for fully coupled thermo-poroelastic analysis of stress distribution around borehole and displacement discontinuity method (DDM) to model fracture deformation. Four models of fracture networks with different facture spacing and varied inclination angle are considered. Permeability variations in underbalanced and overbalanced drilling operations are compared together in different models. The results indicate the difference in effective stress values along x and y directions exceed over 40 MPa around borehole and along fracture surface. It was proved that the mechanical stresses caused by excavation of the rock contribute to short time while fluid pressure and thermal stresses contribute to long term permeability change of fractures. The application of the approach illustrates that the maximum variation of fracture aperture occurs near to the borehole and becomes negligible at large distance away from the borehole. Regardless of the drilling operation method, either overbalanced or underbalanced conditions, the permeability of fractures intersecting borehole decreases for large time after drilling. The maximum variations in fracture permeability occur in fracture network with inclination angle of 45 degrees where maximum variation of effective normal and shear stresses occur. Also, initial poroelastic effect of stresses and fluid pressure on the permeability is maximized by increasing fracture spacing.

1. Introduction

Various types of fluid including oil, natural gas, natural gas liquids, hot water and steam are produced worldwide from fractured sandstone, carbonate and igneous rocks. These fluids are brought to surface through wellbores which are drilled into target formations. These wellbores are also used to inject different kinds of fluid in hydrocarbon bearing formations during secondary or tertiary recovery processes or improving thermal recovery in geothermal reservoirs. The wellbore, therefore, represents one of the most crucial components in the hydrocarbon and geothermal production process, as it is the sole conduit to the reservoir for fluid production or injection. Therefore, understanding the variation of fracture aperture in response to the in-situ stress changes, thermal stress and fluid injection/extraction operations, is important for the successful design and development of petroleum reservoirs and geothermal systems. In particular, it is necessary to understand the mechanisms that cause phenomena such as flow rate of injection and production subject to temperature, pore pressure and in-situ stresses.

Numerous studies have been conducted to probe the effects of excavation process on the rock mass hydraulic conductivity adjacent to the periphery of the excavations (Pusch, 1989; Kelsall et al., 1984; Shen and Barton, 1997). In addition to perturbation caused by excavation process, thermal stress contribution (Dash, 1983; Ghassemi et al., 2003, 2005; Cheng et al., 2001) and fluid pressure effects (Rahman et al., 2002; Shaik et al., 2009) were shown to be significant.

Bai et al. (1997, 1999) examined the stress-dependent permeability of porous-fractured media for the cases where principal stresses were not coincide with the principal permeabilities. Min et al. (2004) investigated the stress-dependent permeability issue in fractured rock masses considering the effects of nonlinear normal deformation and shear dilation of fractures. These numerical experiments showed that the permeability of fractured

* Corresponding author.
E-mail addresses: mgomar@alum.sharif.edu (M. Gomar), goodarznia@sharif.edu (I. Goodarznia), shadizadeh@put.ac.ir (S.R. Shadizadeh).

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rocks decreases with increased stress magnitudes. Latham et al. (2013) performed a numerical analysis on the influence of in-situ stresses on flow processes in fractured rock. The fracture wall displacements and aperture changes were modeled in response to uniaxial and biaxial stress states. Their results presented a mechanically rigorous demonstration that a change in the stress state could cause reactivation of pre-existing fractures and channeling of flow in critically stressed fractures.

A considerable amount of research and experiments on the engineered geothermal systems (EGS) have been carried out worldwide during the past 30 years, which includes fluid circulation and the heat extraction. Kohl et al. (1995) investigated coupled hydro-thermo-mechanical response of a fractured media to force fluid flow in a simple Hot-Dry-Rock (HDR) system. The geometry, a single fracture in a 2D matrix, was chosen to demonstrate the relevant processes for the long term behavior of hot dry reservoir (HDR). Ghassemi et al. (2008) applied poroelastic and thermoelastic concepts to study permeability changes of a single fracture connecting injector and producer wells and showed that induced thermal stresses increases fracture aperture near the injection point; nevertheless, the effects of in-situ stresses was not taken into account. Later on, the investigation of heat extraction and long term effects of cold water injection on geothermal reservoir properties in fractured geothermal systems were conducted by several authors (Koh et al., 2011; Shaik et al., 2011). Xing (2014) applied non-Darcy thermo-fluid flow in an extremely heterogeneous fractured porous medium and substantiate the claim that fractures and their interconnectivities dominate the overall fluid flow patterns and affect the heat transfer in such a fractured porous medium.

Few authors have investigated the effects of induced fluid pressure on naturally fractured rocks on a reservoir scale. Rahman et al. (2002) investigated the shear dilation effect due to fluid pressure on permeability enhancement of naturally fractured reservoirs. Zhang et al. (2007) implemented dual porosity and poroelastic concepts to model stress dependent permeability around inclined borehole by manipulating an experimental-based stress-permeability relationship. Zhou and Ghassemi (2011) developed three-dimensional poroelastic concept to analyze the temporal variation of slip, and opening of a natural fracture in response to its sudden pressurization. Tao et al. (2011) applied poroelastic concept along with discrete fracture approach to study fracture permeability changes in a whole fractured reservoir for isotropic and anisotropic in-situ stress conditions. The result demonstrated that fracture permeability decreases with pressure depletion under isotropic in-situ stress condition and it is likely that shear dilation can improve fracture permeability even if pore pressure decreases under highly anisotropic stress. Atkinson and Thiercelin (1994) analytically examined the behavior of a pre-existing fracture intersecting a pressurized wellbore and revealed that the wellbore pressure and width responses as a function of the length of the open section are extremely sensitive to the location of the fracture with respect to the wellbore. However, all aforementioned studies failed to consider the coupled effect of thermal, fluid pressure and mechanical stresses caused by borehole excavation.

Various flow models (single porosity models, explicit discrete fracture, discrete fracture network (DFN) and continuum approaches (Kim and Deo, 2000)) alongside heat transfer approaches (equivalent temperature concept (Yang and Yeh, 2009), matrix-fracture temperature approach (Bai and Roegiers, 1994) and rock-fluid temperature (Rees et al., 2008; He and Jin, 2010)) were implemented for modeling fluid flow and heat transfer in fractured rocks. An indeterminate number of models have been proposed to simulate the fluid flow in a fractured reservoir and around borehole using the dual porosity concept (Zhang et al., 2007; Lee et al., 1999). Pioneer research on the discrete fracture network model includes Wilson and Witherspoon (1974) and Witherspoon et al. (1980). The dual porosity model requires parameters such as hydraulic conductivity, fluid exchange term and fracture volume fraction, while the discrete fracture network model needs aperture and fracture length.

All former studies confirm that the mechanical and thermal stresses along with fluid pressure have great influence on fracture and rock matrix permeability. Therefore, the main novelty of this article is implementing coupling of all these key factors, thermo-poroelstic concept, to determine the complex behavior of fracture permeability. A new stress state will be initiated around borehole during drilling operation and continuous stress redistributions occur when borehole fluid pressure and temperature alter. Another novelty applied in this study is dynamic modeling of drilling-induced mechanical and thermal stresses along with pore fluid pressure around borehole. These parameters have being localized within a radial ring surrounding borehole and are high enough to cause restriction or improve fluid production or injection. In this study, the permeability of all fractures in the fractured network is modeled simultaneously during drilling operation. Two cases of overbalanced, underbalanced drilling conditions are employed. Discrete-fracture approach is used to develop fluid flow and heat transfer equations in the fractures. Matrix and fracture temperature distribution are treated individually using matrix-fracture temperature concept. Thermal transport by both conduction and advection is included in the fracture and the matrix. Linear elastic effects of temperature and pore pressure perturbations on stress in the solid matrix are assumed as well as a non-linear fracture closure law. Finally, finite element method (FEM) and displacement discontinuity method (DDM) are implemented to calculate unsteady mechanical and thermal stresses beside fluid pressure distribution around borehole and finally modeling fracture permeability.

2. Governing Equations

The relationship between stress–strain and pore pressure for a linear isotropic poroelastic medium is sketched in Biot's theory of poroelasticity (Biot, 1941) which has been reformulated by a number of investigators (Santarelli et al., 1986; Detournay and Cheng, 1988). Thermo-poroelastic stresses can be treated quantitatively within the framework of non-isothermal poroelastic theory, or poro-thermoelasticity (McTigue, 1986; Palciauskas and Domenico, 1982). Using the sign convention of compression positive, the constitutive equation of stress equilibrium is,

$$\nabla.\,\sigma + F = 0 \tag{1}$$

Considering the effect of fluid pressure and thermal stress on the total stress then the governing equation will become,

$$\nabla.\left(\mathbf{C}\colon[\varepsilon - \varepsilon_T]\right) - \alpha_B p \varpi + F = 0 \tag{2a}$$

$$\varepsilon = \frac{1}{2}\left[\left(\nabla u\right)^T + \nabla u\right] \quad ; \quad \varepsilon_T = \alpha_T\left(T - T_0\right) \tag{2b}$$

where σ and u are stress and displacement, ϵ, ϵ_T, α_B, and α_T are total strain, thermal induced strain, Biot's effective stress coefficient and thermal expansion coefficient of rock matrix, respectively, p is fluid pressure, T denotes temperature, F is the summation of all body forces and $\varpi^T = \begin{bmatrix} 1 & 1 & 0 \end{bmatrix}$.

The matrix **C** is called the elasticity matrix and its components are called elastic constants. To account for the effect of fractures in a rock mass system the stiffness matrix needs to be modified depending on the joint spacing and also joint and intact rock elastic

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