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Fully coupled analysis of interaction between the borehole and pre-existing fractures

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ABSTRACT

The coupling of rock and thermal stresses along with fluid pressure are particularly important in fractured rock masses, since stress-induced changes in permeability can be large and irreversible under perturbations resulting from various natural and induced activities. 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. Three cases of overbalanced, underbalanced, and balanced drilling fluid pressure conditions are employed. The application of the approach illustrates that the maximum variation of aperture occurs near to the borehole and become negligible at large distances away from the borehole. It was shown that mechanical stresses caused by excavation of the rock contribute to short time while fluid pressure and thermal stresses are responsible for long term permeability variation of fractures. The results show that the fracture permeability decreases with depletion of the fracture and the rock matrix while increases with pressurization and cooling of fracture during overbalanced condition. The fracture permeability reduces during balanced fluid pressure condition within a short time then enhances by cooling of the rock surrounding the borehole.

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1. Introduction

Prediction of permeability variation close to the underground excavations and in the reservoirs has been one of the most demanding issues in mining, geothermal, and petroleum engineering. Numerous studies have been conducted to probe the effects of excavation process and blasting on the rock mass hydraulic conductivity adjacent to the periphery of the excavations with special reference to the repositories for nuclear waste [1–3]. Thermal stress contribution on the heat recovery and long term permeability variation within hot fractured rock (HFR) for geothermal reservoir systems was shown to be significant [4]. It was found that the injection of cold fluid into a single fracture embedded in an infinite geothermal reservoir induces thermal stress changes more than +40 MPa [5–7]. Kumar et al. [8] examined the temporal variation of fracture aperture in response to the individual and combined effects of thermo-elastic stress and silica dissolution/precipitation; however, changes in fracture aperture and pressure in response to non-uniform cooling were not addressed. Ghassemi et al. [9] applied poroelastic and thermoelastic concepts to study permeability changes of a single fracture connecting injector and producer wells and showed that induced thermal stresses increase 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 [10,11].

Various flow models (single porosity models, explicit discrete fracture, discrete fracture network (DFN) and continuum approaches [12]) and heat transfer approaches (equivalent temperature, matrix-fracture temperature and rock-fluid temperature [13,14]) are used 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 using the dual porosity concept [15]. Pioneer researches on the discrete fracture network model include Wilson and Witherspoon [16] and Witherspoon et al. [17]. The dual porosity model requires parameters such as hydraulic conductivity, fluid exchange term and fracture

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volume fraction while the discrete fracture network model needs aperture and fracture length.

Few authors have investigated the effects of induced fluid pressure on naturally fractured rock on a reservoir scale. Rahman et al. [18] developed a steady state fluid flow model to study the shear dilation effect due to fluid pressure on permeability enhancement. Shaik et al. [19] considered poroelastic stresses in the stimulation of a discrete fracture network by induced fluid pressure. Thermal stresses were not considered in the aforementioned studies. Zhang et al. [20] implemented dual porosity and poroelastic concepts to model stress dependent permeability around inclined borehole by manipulating an experimental based stress-permeability relationship. Tao et al. [21] 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 [22] 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. All aforementioned studies failed to consider the couple effect of thermal, fluid pressure and mechanical stresses caused by borehole excavation.

All former studies confirm that the coupling of rock and thermal stresses along with fluid pressure, i.e. thermo-poroelastic concept, are of great importance in fractured rocks, since stress-induced variations in fracture aperture and as a result rock mass permeability can be significant and irreversible under perturbations resulting from various induced activities. A new stress state around borehole will be initiated during drilling operation and continuous stress redistributions occurs when borehole fluid pressure and temperature alter. Drilling induced stresses, localized within a radial ring around the borehole, are high enough to cause restriction or improve hydrocarbon production or fluid injection.

The novelty of this study lies in its dynamic modeling of the response of a natural fracture intersecting a borehole during drilling operation. Three cases of overbalanced, underbalanced and balanced 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. Finally, finite element method (FEM) and displacement discontinuity method (DDM) are implemented to calculate unsteady stress distribution around borehole and model fracture permeability variation, respectively.

2. Governing equations

To apply discrete fracture approach and matrix-fracture temperature concept, fluid flow and heat transfer models should include two sets of separate equations for both fracture and rock matrix. The governing equations for the single phase flow and heat transfer of a fluid are given by the conservation of mass, energy balance, Darcy's law, and equation of state. To perfectly consider effects of all coupling transport phenomena, the convective and conductive heat transfer and mass fluxes due to dispersion and diffusion are considered in both rock matrix and fracture. Additional information regarding derivation of equations can be found in previous works [9,11,21,23].

$$\nabla.\left(\frac{k}{\mu}\nabla p_m\right)=\beta\frac{\partial p_m}{\partial t}+\alpha\frac{\partial \varepsilon_{vol}}{\partial t}+\beta_m\frac{\partial T_m}{\partial t}+Q_H \tag{1}$$

$$\nabla.\left(w_{fr}\frac{k_{fr}}{\mu}\nabla p_{fr}\right)=w_{fr}\left(\chi\frac{\partial p_{fr}}{\partial t}\right)+\chi_{fr}\frac{\partial T_{fr}}{\partial t}-w_{fr}Q_H \tag{2}$$

$$(\rho c)_{t.m}\frac{\partial T_m}{\partial t}+(\rho c)_f\left(v_{f.m}.\ \nabla T_m\right)=k_m\nabla^2T_m-Q_T \tag{3}$$

$$(\rho c)_{t.fr}\frac{\partial T_{fr}}{\partial t}+(\rho c)_f\left(v_{f.fr}.\ \nabla T_{fr}\right)=k_{fr}\nabla^2T_{fr}+Q_T \tag{4}$$

The multipliers β,β_m, χ,χ_{fr}, $(\rho c)_{t.m}$, $(\rho c)_{t.fr}$, k_m, $k_{fr}$are defined as:

$$\beta=\left(\alpha-\phi_m\right)c_{s.m}+\phi_m c_f \tag{5}$$

$$\beta_m=\alpha\beta_s+\phi_m\left(\beta_f-\beta_s\right) \tag{6}$$

$$\chi=\phi_{fr}c_f+\left(1-\phi_{fr}\right)c_{fr} \tag{7}$$

$$\chi_{fr}=\left(\alpha-\phi_{fr}\right)c_{fr}+\phi_{fr}c_f \tag{8}$$

$$(\rho c)_{t.m}=\left(1-\phi_m\right)(\rho c)_{s.m}+\phi_m(\rho c)_f \tag{9}$$

$$(\rho c)_{t.fr}=\left(1-\phi_{fr}\right)(\rho c)_{s.fr}+\phi_{fr}(\rho c)_f \tag{10}$$

$$k_{fr}=\left(1-\phi_{fr}\right)k_{fr}+\phi_{fr}k_f \tag{11}$$

$$k_m=\left(1-\phi_m\right)k_m+\phi_m k_f \tag{12}$$

The (Eqs. (1) and 2) model fluid flow in rock matrix and fracture while (Eqs. (3) and 4) are governing equations of heat transfer in matrix and fracture, respectively. The thermal conductivity, k_{fr}, and compressibility, c_{fr}, of the gauge material filling the fracture are assumed to be equal to those of rock matrix.

A characteristic feature of the non-steady-state motion of a liquid in fractured rocks is the exchange of heat and mass between the blocks and the fissures; to account for these effects, the terms Q_H and $Q_T$are allocated for fluid flux and heat transfer between two media. The matrix-fracture transfer term can be defined by two different approaches: one approach includes using matrix shape factors [24] and the other is based on boundary conditions imposed explicitly on matrix surface [23]. For the present study, since temperature and pressure rapidly come into equilibrium in the highly permeable fracture on the fracture spacing scale, therefore, this equilibrium is defined in terms of the boundary condition in the matrix equations. Same analogy as matrix-fracture transfer term is applied to the term Q_T in heat transfer.

The relationship between stress-strain and pore pressure for a linear isotropic poroelastic medium is given by Biot's theory of poroelasticity [25] and developed further by various authors [26–28]. Constitutive equation for thermo-poroelastic theory were developed by extending the classic Biot's poroelastic theory for the non-isothermal case [29,30]. Using the sign convention of compression positive, the constitutive equation of stress equilibrium is,

$$\nabla.\ \sigma+F=0 \tag{13}$$

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

$$\nabla.\left(\mathbf{C}:\ [\varepsilon-\varepsilon_T]\right)-\alpha_B p\varpi+F=0 \tag{14}$$

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