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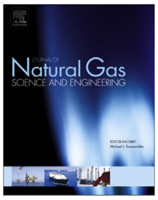

A fully coupled thermo-hydro-mechanical, three-dimensional model for hydraulic stimulation treatments

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ABSTRACT

In this study, we developed a fully coupled thermo-hydro-mechanical (THM), three-dimensional model to simulate hydraulic fracturing (HF) treatments. Using the pseudo-continuum approach, we extended the classical THM constitutive equation into an anisotropic formulation for the purpose of capturing the effects of fracture sets. Consequently, the dynamic process of fracturing propagation can be modeled for both tensile and shear failures. The fluid flow terms with tensor permeability, or heat transfer terms with tensor conductivity, are calculated using the Multi Point Flux Approximation (MPFA) L-method. The model is capable of predicting the detailed permeability distribution within the stimulated reservoir volume (SRV), while also considering the fluid leak-off and thermal stresses. To verify the developed THM code, we compared its numerical solutions with some other reliable solutions in several benchmark cases. Specifically, the dynamic fracturing propagation modeling is verified by the KGD model. Finally, the code is used to investigate the complicated multi-physical HF processes. The results show that the geometry of hydraulic fractures is affected by the following factors: *in-situ* stress, anisotropic permeability, heterogeneity, thermal stress, shear failure, and the stress shadow effect, not all of which can be considered with the conventional HF models due to the over-simplification employed.

1. Introduction

The study of geomechanical behaviors, focusing on evaluating the interplay between stress, pressure, temperature, mechanical properties, natural fractures and hydraulic fractures in rock mass, has attracted extensive attention due to its critical role in characterization and development of oil and gas fields. Nevertheless, conventional reservoir simulators only introduce a simple parameter, i.e., pore compressibility, for porosity modification, which is not adequate to consider realistic geomechanical effects. For some stress-sensitive reservoirs, such as under-compacted, highly compacted, faulted and fractured reservoirs, geomechanical effects can be dominant to the porous media flow. In under-compacted reservoirs, depletion will increase effective stress applied on matrix grain, which gradually leads to pore-collapse, known as shear compaction (Chin et al., 1993). The constitutive behavior of under-compacted reservoir rocks is nonlinear, elastoplastic, and strongly depends on stress path and temperature (Longuemare et al., 2002). In fractured reservoir operations, such as waterflooding (Chin and Nagel, 2004; Heffer, 2002), nuclear waste disposal (Chijimatsu et al., 2000; Tsang et al., 2012), CO_2 sequestration (Hawkes et al., 2005; Rutqvist, 2012), coalbed methane (CBM) extraction (Liu et al., 2011; Wei and Zhang, 2010), geothermal exploitation (Hu et al., 2013; Kelkar et al., 2014), and HF treatments (Abousleiman et al., 2014; Nassir et al., 2010), geomechanics also play a vital role. The closure and reopening of natural fractures resulting from changes in pore pressure significantly affect the fluid flow within the porous media. Moreover, lowering the effective normal stress on pre-existing fault planes can induce slip, and result in subsidence, as well as trigger different magnitudes of earthquakes.

To solve the complex THM coupling system successfully, two main domains that should be taken into consideration seriously are numerical method and solution strategy. Most common numerical methods can be divided into three categories, as continuum methods, discontinuum methods, and hybrid methods (Jing, 2003). The cell-centered finite volume method (FVM) is widely used in the reservoir simulation (Aziz and Settari, 1979; Cao, 2002); and the node-based finite element method (FEM) is very popular in the geotechnical engineering and thermomechanics communities (Lewis and Sukirman, 1993; White and Borja, 2008). Then, mixed

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finite element methods (MFEM) were proposed to solve the THM coupling system for the purpose of eliminating the oscillation of pressure at an early time and guaranteeing local conservation of mass and energy. Extended finite element methods (XFEM) are quite useful for predicting the initiation and propagation of fissures and fractures within geomaterials. In addition, the combination of finite element and finite volume methods (FEFVM), which have the same advantages as MFEM, was presented to address THM problem (Kim et al., 2012). For multiphysics problems, choosing an appropriate solution scheme can be very valuable. Until now, there are four main types: fully coupled, iteratively coupled, explicitly coupled and loosely coupled, which have been proposed, implemented, and investigated by many authors (Gai et al., 2003; Jha and Juanes, 2007; Kim et al., 2009). Each type of coupling possesses its own advantages and disadvantages, and which one should be chosen depends heavily on the kind of problems to be solved and authors' focuses (e.g., accuracy, adaptability, or running speed) (Tran et al., 2009). Among these methods, the fixed-stress split the scheme of the iteratively coupled method was strongly recommended (Asadi et al., 2014; Kim et al., 2009) because of its unconditional convergence, similar accuracy to a fully coupled method, and relatively high running speed.

It is widely acknowledged that multiple-fracture treatments in horizontal wells constitute the key techniques to achieve economical production from tight and shale gas reservoirs (Fisher and Warpinski, 2012; Warpinski et al., 1993; Wu and Olson, 2015). This is because these technologies dramatically increase the contact area between fractures and reservoirs with ultra-low permeabilities to improve well performance. Many sophisticated fracture diagnostic techniques, such as microseismic, tilt meters, temperature logging and tracers, have already been utilized to identify the induced fractures. However, these techniques provide little insight into the dynamic process of fractures propagation, hydraulic fracture area, and detailed permeability distribution within SRV. Therefore, numerical modeling can constitute an important tool for engineers to further understand the hydraulically stimulated reservoirs. Recently, valuable studies have been carried out by many authors in modeling the complex HF processes. For example, Xu et al. (2010) presented a semi-analytical wiremesh model to characterize and predict the growth of induced hydraulic fracture networks. Meyer and Bazan (2011) developed a Discrete-Fracture-Network (DFN) model, which was capable of considering fracture interaction, proppant transport, and planar fracture propagation in the principle stress. DFN model was also employed by McClure and Horne (2014) to investigate shear-induced enhancement of permeability and interaction between hydraulic fractures and natural fractures. Although the DFN model could provide us with insight into complex fluid flow and transport phenomena in porous media with discrete, connected fractures, it is difficult to integrate thermal effects and mechanical deformation (Jalali and Dusseault, 2012). An explicit flow/geomechanics/failure model (Nassir et al., 2014) was developed using FEM to incorporate both tensile and shear failure to HF. Dahi-Taleghani and Olson (2011) presented a complex hydraulic fracture propagation model based on XFEM via introducing a discontinuous interpolation function. Similar to XFEM, the rock discontinuous cellular automaton method (Pan et al., 2014) was proposed to track crack surface and crack front. Although XFEM is able to describe each single fracture initiation, propagation, and resulted fracture geometry and does not rely on the remeshing method, applications in full 3D problems are still very challenging because relevant studies mainly focused on 2D problems, and the coupling of flow and geomechanics by XFEM has not extensively been investigated (Kim and Moridis, 2013). Ji et al. (2009) proposed a numerical algorithm for HF, in which the node splitting technique was first adopted to deal with rock failure. Kim et al. (2014) employed a similar idea to study vertical fracture propagation by continuously updating boundary conditions and data connectivity, in which both shear and tensile failures were incorporated. However, using a large, constant permeability for fractured blocks was not sufficient to describe the dynamically mechanical behaviors of fractures accurately; introducing stress/pressure dynamic transmissibility multipliers was no more applicable when the permeability was in a full tensor form (Bagheri and Settari, 2008). Many existing HF models seemed to neglect the thermally-induced stress. However, studies by Tran et al. (2013) and Goodarzi et al. (2013) suggested that cooling-induced stress could largely increase net pressure (fluid pressure minus minimum *in-situ* stress) to crack formation under the same pore pressure condition and could increase the speed of fracture propagation. Moreover, thermally-induced secondary fractures perpendicular to main fractures could effectively improve production well performance.

In this work, we employed FEFVM (Kim et al., 2009) for space-discretization to solve the THM coupling problems in a single integrated code of C++. For fluid-heat flow, the locally conservative MPFA L-method (Aavatsmark et al., 2008, 2010; Wolff et al., 2013) was implemented for finite volume discretization. This technique is capable of circumventing numerical oscillation, as well as eliminating the grid orientation effects (Li et al., 2015). For the displacement field, the FEM was adopted to track the continuous deformation. While the tensile or shear failure criterion was met, incorporating thermal stress, the pseudo-continuum approach (Bagheri and Settari, 2008; Nassir et al., 2014) was used to homogenize the stiffness and permeability of the fractured block. The hyperbolic relationship between fracture deformation and normal effective stress proposed by Bandis et al. (1983) and Nassir et al. (2014) could help determine fracture permeability and stiffness. Because the modification of permeability will cause changes of the transmissibility connection list, which further alters the Jacobian matrix structure associated with fluid-heat flow, we have to recalculate the transmissibility connection list and then reconstruct the Jacobian matrix for fractured block in each Newton step to capture the response of the nonlinear mechanical behavior of fractures.

To verify the developed code as a whole, we first present four benchmark examples, including three analytical solutions and one example problem calculated by a commercial simulator, to verify the fully coupled THM modeling where new fractures were not allowed to generate. Then, the KGD model is used to test the performance of code for HF problems. Finally, we present three application examples: (1) hydraulically fractured vertical well; (2) perforation scheme for multilayered reservoirs based on real data; and (3) multifractured horizontal well. Results illustrate that HF-induced fractures are usually asymmetrical, resulting from anisotropy of permeability, *in-situ* stress and rock strength, and that the thermal stress, shear failure, and the stress shadow effect are of significant importance for HF treatments.

2. Approach and implementation

2.1. Governing equations for coupled THM model

We treat the porous medium as the superimposition of two continua, i.e., the skeleton continuum and the fluid continuum. The physical model is based on thermoporoelasticity theory (Coussy, 2004). We assume that the porous medium is of anisotropy and of infinitesimal transformation, and that the pore fluid is non-isothermal, single-phase, and compressible. The governing equations for fluid and heat flow, and mechanics are obtained from mass, energy, and linear-momentum balances, respectively.