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Geomechanics Coupled Reservoir Simulation using a Hybrid EDFM and MINC Model for Unconventional Reservoirs

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Abstract

Currently, two unresolved challenges encountered in unconventional reservoir simulation are: (1) accurately modeling complex interaction between hydraulic fracture, natural fracture and tight matrix; (2) efficiently couple geomechanics with fluid flow in fractured reservoirs. The objective of this study is to couple geomechanics with two hybrid fracture models built on distinct methodologies of combining Embedded Discrete Fracture Model (EDFM) and Multiple INteracting Continua (MINC), so that a better model for simulation can be selected and the geomechanical impact on unconventional reservoir development can be observed and evaluated.

A geomechanics coupled EDFM has been developed to investigate how stresses and strains could affect fluid flow in fractures and matrix. Fluid flow and geomechanics were fully coupled in an Integrated Finite Difference (IFD) approach in this model. A new extension of this model to couple geomechanics for combined EDFM and MINC is developed. With the implementation of hybrid EDFM and MINC model, this coupled simulator can be leveraged to describe the complex fluid flow interaction between hydraulic fracture, natural fracture and tight matrix, under the influence of geomechanics. In this study, two hybrid models are compared with each other, and also with analytical solution and refined grid model: one is the embedded discrete fractures intersected with classical nested MINC blocks and the other is the MINC partition conforming the discrete fractures geometry and following the iso-pressure profile. These cases are compared in terms of oil production rate, cumulative production and pressure decline distribution.

The comparison results show that the second hybrid model is capable of better capturing the transient and long-term behavior, especially when geomechanics is taken into account. Several scenarios are investigated and interpreted: (1) changing the stimulated reservoir volume where both hydraulic and natural fractures are activated; (2) changing the number of continua and grid block size in two hybrid models and seek the optimal combination to accurately capture the transient flow behavior. The

comparison of cases with and without geomechanics coupling can be utilized to observe its effects on cumulative productions and short- and long-term production rates. This coupled model is built on a parallel computing framework so it is also desired to examine the scalability of the model for large scale problems with complex fracture networks.

Introduction

All submitted papers will be reviewed to ensure they are free from commercialism and significant errors, but will not be edited or re-typed. Papers must be at least four (4) pages and not more than twenty (20) pages in length. All papers, regardless of length, should include the key elements of a technical paper, such as references, comparisons to related works and other details expected in a research paper but not in an abstract.

Coupled fluid flow and geomechanics model is essential to accurately model the injection/production process in unconventional reservoirs, not only due to the fact that hydraulic fractures and natural fractures are highly sensitive to geo-stresses, but also the multiphysics interaction between high permeable fracture and tight matrix (Rutqvist et al., 2002; Wang et al., 2015). Embedded Discrete Fracture Model (EDFM) has been widely used in unconventional reservoir simulation, especially for the purpose of building a fracture system without reconstructing the modeling mesh (Lee et al., 2001; Moinfar et al., 2012). In unconventional reservoirs, existing natural fracture system add an extra complexity to fluid flow modeling as a path from tight matrix to hydraulic fracture. Multiple-INteracting-Continua(MINC) is often adopted for a highly fractured system with multiple continuums (Ding et al., 2018). MINC, thus, is a proper candidate for unconventional reservoirs where natural fractures are considered cutting through tight matrix. In order to capture hydraulic fracture generated by stimulation, EDFM can then be introduced into this system, cutting the original tight matrix and intersecting with the natural system.

In this study, a fully coupled fluid flow and geomechanics model was developed for this hybrid fracturing system integrating EDFM and MINC, based on a parallel computing framework TOUGH2-CSM (Winterfeld and Wu, 2011, 2016). The discretization of mechanical governing equation is based on an Integral Finite Difference (IFD) approach where the linear elasticity and static equilibrium equation are transformed to a momentum balance equation. A three-dimensional EDFM (Wang et al., 2020) has been improved and incorporated with MINC. Multiple continua within a grid block have the same stress state and normal stress acting on embedded fractures can be computed, as well as the stress (or strain) dependent fracture permeability. A tight oil reservoir case study was investigated by the developed model using a synthetic hydraulic and natural fracture system. To observe the impact of geomechanics, fluid flow without geomechanics coupling was compared with fully coupled results. A few parameters were adjusted to see how the reservoir system responded, such as the partition number of MINC, mechanical parameters of the continua and the injection/production rate/pressure.

Theory and/or Methods

Mathematical Model of Fluid Flow and Geomechanics

Fluid flow in porous media is governed by mass balance equation (1), where M^k, $\overrightarrow{F^k}$ and Q^k are accumulation term, flux term and sink/source term of component k respectively.

$$\frac{d}{dt}M^k = -\nabla \cdot \overrightarrow{F^k} + q^k \tag{1}$$

Specifically, accumulation term is the mass fraction of a component within the pore space

$$M^k = \phi \sum_{\beta} S_\beta \rho_\beta X_\beta^k \tag{2}$$

And flux term between grid blocks are calculated by Darcy's flow in equation (3)

$$\overrightarrow{F^k}\big|_{adv} = \sum_{\beta} X_\beta^k \overrightarrow{F_\beta} = -\sum_{\beta} X_\beta^k \, k \frac{k_{r\beta}\rho_\beta}{\mu_\beta}\left(\nabla P_\beta - \rho_\beta \vec{g}\right) \tag{3}$$

The momentum balance governing equation (6) for mechanics is derived from linear elasticity (4) and static equilibrium (5):

$$\bar{\tau} - h(P)\bar{I} = 2G\bar{\varepsilon} + \lambda(tr\bar{\varepsilon})\bar{I} \tag{4}$$

$$\nabla \cdot \bar{\tau} + \overline{F_b} = 0 \tag{5}$$

$$\frac{3(1-\nu)}{1+\nu}\nabla^2\tau_m + \nabla \cdot \overline{F_b} - \frac{2(1-2\nu)}{1+\nu}\nabla^2[h(P)] = 0 \tag{6}$$

where the mean stress can be correlated with volumetric strain:

$$K\varepsilon_{v,n} = \tau_{m,n} - \sum_{j}\left(\alpha_j p_{j,n}\right) \tag{7}$$

$$h(P) = \sum_{j}\left(\alpha_j P_{j,n}\right) \tag{8}$$

This momentum balance equation (7), with a similar form as mass/energy balance (1) is then handled by IFD approach. The main advantage of this approach is developing the coupled model without much modifying the program structure or parallelization schemeEquation (7) indicates that all continua in a grid block have the same stress and the total volumetric strain is dependent on the variables of all continua. This equation can be partitioned into an extended version of Beltrami-Michell equation where stress tensor components are treated as primary variables of governing equations. We will solve for all stress tensor components in the numerical solutions.

Approaches of Coupling Fluid flow and Geomechanics

Discretization of the above governing equations using IFD can be summarized as below:

$$\begin{aligned}&\frac{d}{dt}\left(M_n^k V_{n,0}\left(1-\varepsilon_{v,n}\right)\right)\\&= -\sum_{m}\sum_{\beta} -k_{nm}\left(\frac{k_{r\beta}\rho_\beta X_\beta^k}{\mu_\beta}\right)_{nm}\left(\frac{P_n + P_{c\beta,n} - P_m - P_{c\beta,m}}{D_{n,0}\left(1-\varepsilon_{D,n}\right) + D_{m,0}\left(1-\varepsilon_{D,m}\right)}\right.\\&\left.- \rho_{\beta,nm} g_{nm}\right) A_{nm,0}(1-\varepsilon_{A,nm}) + q_n^k V_{n,0}(1-\varepsilon_{v,n})\end{aligned} \tag{9}$$

for mass balance equations and,

$$\sum_{m} A_{nm,0}(1 - \varepsilon_{A,nm}) \left\{ \frac{\left\{ \begin{array}{c} \tau_{m,+} - \tau_{m,-} + \frac{s_+(1+\nu_+)}{3(1-\nu_+)} F_{b,+} + \frac{s_-(1+\nu_-)}{3(1-\nu_-)} F_{b,-} \\ -\frac{2(1-2\nu_+)}{3(1-\nu_+)}\left(h(P)_+ - h(P)_{+,int}\right) - \frac{2(1-2\nu_-)}{3(1-\nu_-)}\left(h(P)_{-,int} - h(P)_-\right) \end{array} \right\}}{\frac{s_+(1+\nu_+)}{3(1-\nu_+)} + \frac{s_-(1+\nu_-)}{3(1-\nu_-)}} \right\}_{\tau,nm} = 0 \quad (10)$$

for mean stress equations (using an explicit interfacial variable approach, + represents one grid on one side of connection interface and – represents the other). As it can be seen, the mass balance equations are dependent on volumetric and normal strains of a grid block; the stress equations are coupled with fluid flow because of the pressure related term. Due to the fact that strains are Figure 1balance equation should produce a term in non-neighbour block in Jacobian matrix, which is handled in our model.

Embedded Discrete Fracture Model

Embedded discrete fracture model is constructed by geometrical computation of intersection between planes and cubes in three-dimensional space. The planes are discrete fractures which are cut into polygons by grid blocks, as shown in Figure 1. Connection distance are established using a volumetric weighting method.

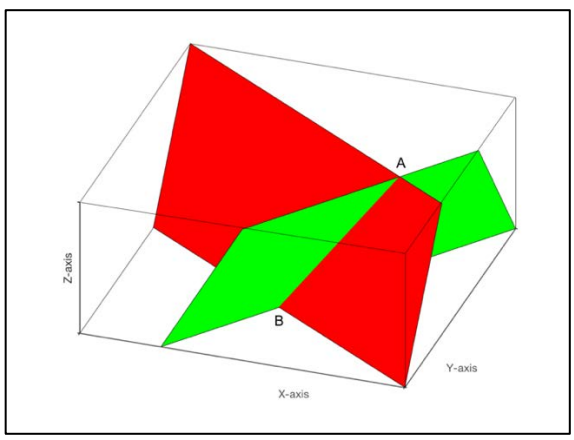

Figure 1 Discrete fracture polygons and its matrix grid block

When we consider integrating EDFM and MINC, embedded discrete polygons are intersecting with internal MINC blocks as well, shown in Figure 2. The constructing approach will be iterated within a grid block among all MINC blocks. Although discrete fractures have the same stress state with the grid block and both fracture and matrix continuum, the effective stress acting on the two discrete fracture faces (orange and green) could be distinct since the pore pressure in two continuums are not necessarily the same.

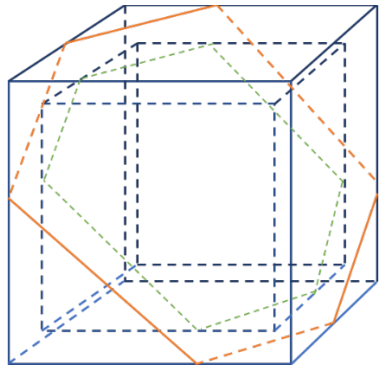

Figure 2 Discrete polygon intersecting with MINC blocks

In order to follow the general purpose of MINC, which describes the equipotential pressure contour away from the fracture face, there exists another model (Ding et al., 2018) as shown in Figure 3. The MINC partitioning conforms with the geometrical shape of embedded discrete fractures. These two meshing approaches are both compatible with our coupled model and they are both tested in the case study.

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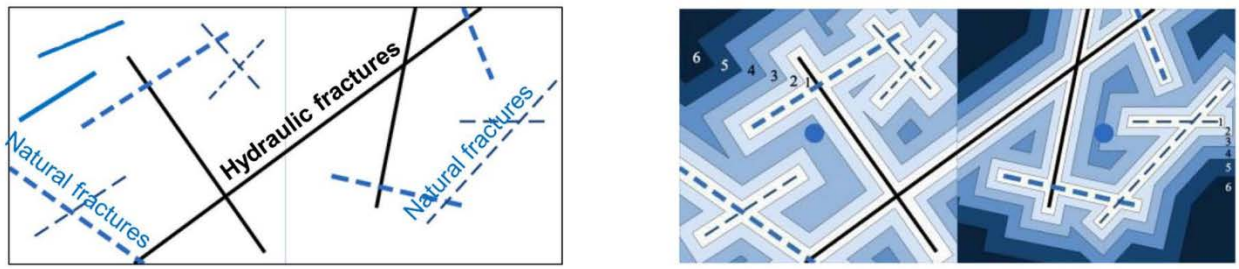

Figure 3 MINC partition along embedded discrete fractures

Results and Discussions

The simulation model has been developed and still under debugging and testing stage. The results and discussions will be in the full manuscript.

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