COUPLED APPROACH DEM/CFD FOR MODELLING HYDRAULIC FRACKING PROCESS IN ROCKS

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1. General

Hydraulic fracking is a well stimulation technique to increase the productivity of petroleum reservoirs in which rocks are fractured by a pressurized liquid. The process involves the high-pressure injection of fluid (primarily water, containing sand or other proppants suspended with the aid of thickening agents) into a wellbore to create cracks in the deep-rock formations through which natural gas and petroleum will flow more freely. When the hydraulic pressure is removed from the well, small grains of hydraulic fracturing proppants hold the fractures open. The modelling of the fluid-driven fracture propagation into rocks comprises the coupling of different physical mechanisms, including deformation of the solid skeleton induced by the fluid pressure on fracture surfaces, flow of the pore fluid along new fractures and through the region of surrounding existing fractures and pronounced heat changes.

There are two main approaches for modelling the propagation of hydraulically driven complex fracture patterns: continuum-based models and discontinuous meso-scale models at the grain level. The continuum-based meso-scale models are obviously unable to fully render meso-scale coupled thermal-hydraulic-mechanical effects. As compared with conventional continuum mechanics methodologies used in most of existing numerical studies, discontinuous meso-scale models at the grain level (such as the discrete element method (DEM)) are more realistic since they allow for a direct simulation of meso-structure and are very useful for studies of the mechanism of the initiation, growth and formation of fractures [1], [2]. The commonly used approach to describe fluid flow and predict interaction mechanisms between flowing fluid and particles is the pore-network modelling, assuming that fluid flows through channels connecting pores that accumulate pressure. In this approach, a simplified laminar viscous Poiseuille flow [3] or Stokes flow [4] are usually assumed. The pore network model is built through a weighted Delaunay triangulation over the discrete element packing. The finite volume method is usually applied to solve the governing equations of motion. [3]. The model may describe incompressible [5] or compressible fluids [6].

Most of coupled DEM/CFD approaches meet the following simplified assumptions [3]: isothermal conditions, single phase flow, laminar fluid flow in pores and fractures and small grains displacements in rocks. In the paper, a significant extension of the pore-network model is proposed (called virtual pore network (VPN)).

2. Fluid flow model and coupled DEM/CFD simulations

The VPN model accurately reproduces grains and voids geometry (pores and fractures). The voids and fractures (fluid domain) are discretized with the aid of triangular (in 2D) or tetrahedral (in 3D) control volumes (called the virtual pores). Similarly as in the pore-network method, the virtual pores are connected by channels that connect their gravity centres The virtual pores are connected by channels that connect their gravity centres. Fluid flows in channels while virtual pores accumulate pressure and volume fraction of phases. The Poiseuille flow model is assumed in channels. To model multiphase flow of compressible fluid, the fluid volume (VOF) model [7] was implemented. VOF is a surface-tracking technique applied to a fixed

Eulerian mesh and can simulate two or more immiscible fluids by solving a single set of equations. Hence, the Poiseuille flow equation can be expressed for 3D problems and secondary-phase fluids as:

$$\frac{\partial}{\partial t}\left(\alpha_q \rho f_q h\right) = \frac{\partial}{\partial x}\left(\frac{\alpha_q \rho_q h^3}{12\mu_q}\frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{\alpha_q \rho_q h^3}{12\mu_q}\frac{\partial P}{\partial z}\right), \quad (1)$$

where index q denotes the liquid phase, α_q is the volume fraction, ρ_q is the density, h is the hydraulic channel aperture, μ_q is the dynamic viscosity and P denotes the pressure. Equation 1 is not solved for the gas phase that is computed based on the following constraint $\sum_{q=1}^{2} \alpha_q = 1$. In order to capture large grain displacements in rocks, a special transformation algorithm was applied, based on the assumption that mass is a topological invariant. This algorithm transforms simulation results computed for the old grid into the new grid that may be significantly geometrically deformed. It enables to investigate fluid flow in topologically variable pores and fractures (i.e. some pores and fractures may vanish and new ones may appear).

The mesoscopic mechanical constants for rocks were calibrated with preliminary DEM simulations of uniaxial compression and splitting tension [2]. The rock material was described as a 3-4-phase material. VPN was calibrated by simulating permeability tests. The series of numerical coupled DEM/CFD analyses were performed to study the process of filling pores and fractures with the fracturing fluid in rock specimens. The influence of the fluid pressure, fluid velocity, initial rock porosity, location and number of existing discontinuities (faults, joints, bedding layers) on the initiation and propagation of hydraulic fractures was carefully investigated. The numerical results were qualitatively in agreement with the experiments with respect to the fracture pattern.

3. Conclusions

In contrast to commonly used pore-network approaches, VPN reproduces more realistically fluid flow in pores and fractures in rocks and enables also to investigate multi-phase fluid flow. A strong relationship between the initial fraction of the liquid phase in pores and fractures and the propagation speed of the hydro-fracking process was observed in coupled DEM/CFD analyzes. The impact of initially existing discontinuities in rocks on the hydraulic fracture geometry was pronounced.

4. References

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