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Coupled Simulation of Geomechanics and Multiphase Flow in Fractured and Faulted Rock Masses with Application to Petroleum Reservoirs

A . (Tony) Settari (1,2), D. A. Walters (2) and M.A. Bagheri (3)

(1) Dept. of Chem. And Petrol. Engineering, University of Calgary

(2) TAURUS Reservoir Solutions Ltd., Calgary

(3) Sproule International Ltd., Calgary

Complex coupled processes involving mutiphase flow in porous media, geomechanics of rock mass and thermal effects are important in many branches if geosciences. Such Thermo_Hydro_Mechanical (THM) processes are important in many situations in petroleum engineering. Examples are compaction and ground subsidence in compacting reservoirs, fault reactivation by production, thermal recovery processes in unconsolidated sands, injection of fluids at high pressure (leading to propagation of induced fractures), integrity of wellbores and reservoir-shale interfaces (see Settari, 2003, for examples). Related problems include disposal of drilling waste, storage of radioctive and other hazardous materials, CO2 sequestration in aquifers, etc. (Stephansson et al., 1996).

Many of these processes take place in fractured (jointed) media that may also include faults. While the modeling techniques for flow in dual porosity/permeability media, and for thermal modeling of flow are highly developed and in common use, modeling of the mechanical response of jointed media in a coupled manner is still developing.

This paper describes a comprehensive model of coupled multiphase flow, thermal, and jointed (fractured) rock geomechanical phenomena. The basis of the model is the modular concept developed by the authors since 1990's and its recent extension to the dual porosity treatment of solid modeling (Bagheri and Settari, 2008).

The overall structure of this simulation system includes two major modules. The solution of multiphase flow and heat transfer is carried out by means of a conventional reservoir simulator for dual porosity/dual permeability porous media. Flow in both systems (fracture and matrix) is solved using finite difference techniques that are standard in reservoir simulation, and the mass transfer between them is based on the Warren-Root type transfer functions. The coupling with the solid mechanics (geomechanics) model is achieved by re-formulating the porosity as a function of stress, pressure, temperature and volumetric strain. The stress solution module is an finite element (FEM) model. The rock mass can be represented by any number of regular joint sets with different properties (based on a Barton-Bandis joint model). The deformations and stresses of the jointed rock are then solved as a pseudo-continuum, using the generalization (and correction) of the method of Huang (1995). The strains of matrix and fractures are then decoupled and used in porosity and permeability coupling terms with the flow/thermal solution. The well established iterative algorithm is used to solve the flow-stress system during a time step.

The novelty of this approach lies in the fact that both the flow and deformation equations are solved as a fractured system. In the past, typically only one component would be solved as fractured, while the other would be simplified as a continuum.

The paper will describe the above model conceptually and then focus on two novel features of the formulation:

- Coupling of flow and stress through dynamic calculation of the flow permeability tensor
- Compressibility issues in coupled modeling

Two methods of coupling the permeability are proposed and compared using a fractured reservoir example. It is shown that, for fracture sets of arbitrary dip and strike, the deformation leads to a change in both the direction and magnitude of the permeability tensor, and becomes transient. This in turn requires full tensor discretization of the flow equation, with a corresponding penalty in computing time.

Reservoir (pore volume) compressibility is an important parameter controlling pressure decline and recovery in depletion processes. The apparent compressibility may be measured indirectly from the reservoir response. For coupled modeling, such data constrains the fracture characterization obtained from geology, borehole imaging, DFM, etc. analysis On the other hand, it is important to be able to derive correct reservoir compressibility for use in uncoupled flow modeling. A method has been developed to relate the pore volume compressibility in the flow model and individual fracture properties (frature set porosity, spacing, stiffness, orientation and effective stress state). The method has been successfully applied on a large, complex fractured field in Europe.

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