NFflow Reservoir Simulation for Representing Coupled P & T Effects on Fractures

W. Neal Sams[1,2]
US Department of Energy, National Energy Technology Laboratory, Morgantown WV; [2]AECOM Corporation

Research & Innovation Center

NATIONAL ENERGY TECHNOLOGY LABORATORY

Abstract

Discrete fracture network flow simulators are arguably the best platforms for T&P calculations, geochemistry, and mechanical behavior modeling along natural fracture flow pathways in unconventional reservoirs. Thus, NETL's discrete fracture reservoir simulator, NFflow, is being modified to simulate non-isotherm conditions. The fracture segments that were previously represented as single elements are now subdivided both vertically and horizontally to model heat transport within the fractures. The rock matrix surrounding each fracture segment that was previously modelled by a one-dimensional model has been replaced by a three-dimensional model, which is also extended vertically to include rock above and below the reservoir layer.

The work is being done in stages. The first stage has included the new gridding algorithm for the fractures and surrounding rock and the development of an indexing scheme capable of describing the new geometric complexity. An energy balance was added that describes the convective energy transport in the fractures, the conductive energy transport in the rock matrix both horizontally and vertically, and the exchange of energy between the rock and fluid phases. In the first stage of the project the thermodynamics is restricted to a liquid as the fluid phase and the fluid flow is restricted to the fractures. In a later stage the thermodynamics will extended to gases and supercritical fluids and the flow equations extended to include fluid interchange between the fractures and rock matrix. NFflow is intended for use on personal computers, rather than super computers, making it more widely available to all potential users.

Definitions

$\mathbf{T}$ = fluid temperature	θ = rock temperature
P = pressure	ρ = mass density
μ = viscosity	Z = compressibility factor
b = fracture aperture	φ = void fraction
k_r = thermal conductivity of rock	$k_f = \frac{b^2}{12}$ = transmissibility of fracture

$(\rho c_p)_l$ = liquid heat capacity

$(\rho c_p)_{eff} = \varphi(\rho c_p)_l + (1-\varphi)(\rho c_p)_r$ = effective heat capacity

$\vec{v}$ = velocity vector

u & w = superficial fluid velocity, x_direction & y_direction

Q_i = mass flow rate through a node in the direction i, positive away from node

q_i = energy flow rate from the direction i, positive into the fracture midpoint

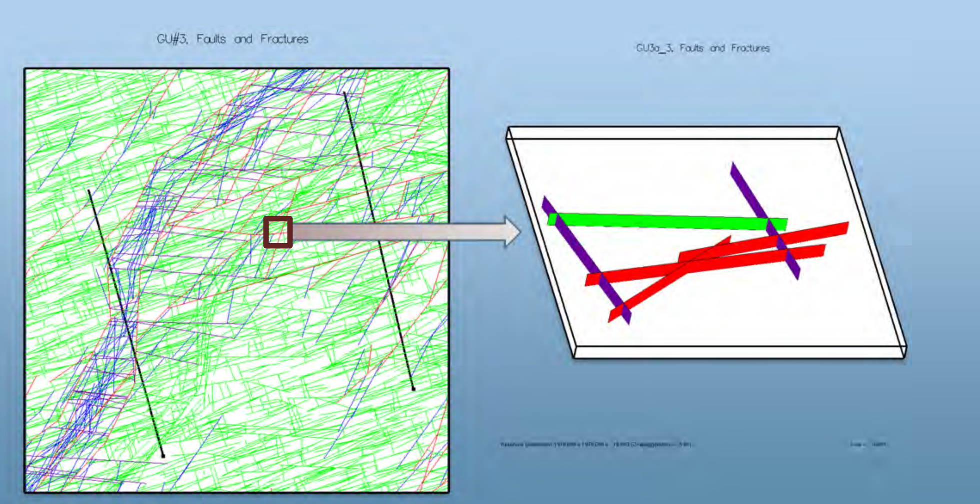
$\hat{u}$ = specific internal energy

Problem Becomes Much More Difficult

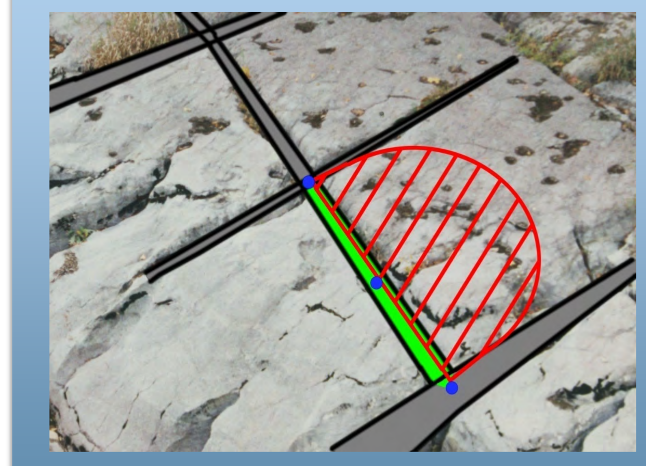
- Added equations for energy.
- Domain for energy problem much larger than domain for mass flow problem.
- Because equivalent volume problem has expanded to three dimensions, previous decomposition not possible. Variables at all locations must be solved simultaneously.
- Pseudo-potential is now a function of temperature, and a new solution technique is necessary. The linear equations lose their simple form.
- The number of solution variables increases by one or two orders of magnitude.
- But the linear equations still have the form where the equation for a mass or energy balance at one location is coupled at most to six other points.

Pre-existing Model

Fracture Network



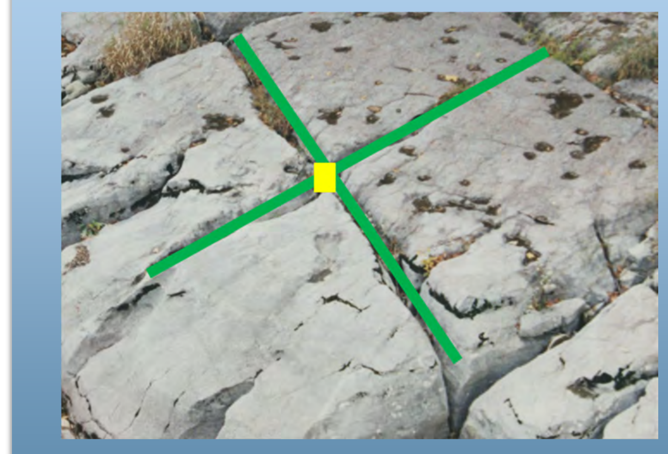
The Rock Matrix



- Inter-granular flow is modeled with Darcy's Law
- 1-D approximation: only communicates with adjacent fracture segment
- Simplified to effective volume
- Each of these problems is solved independently

$$A\frac{\partial \varphi\rho}{\partial t} + \frac{\partial A\rho u}{\partial x} = 0$$

Flow Path Intersections



- Zero-volume, no accumulation term
- Fracture flow modeled as flow between two parallel plates
- Reduce problem by calculating the pseudo-potential at these points

$$Q_{I-s} + Q_{I-n} + Q_{I-w} + Q_{I-e} = 0$$

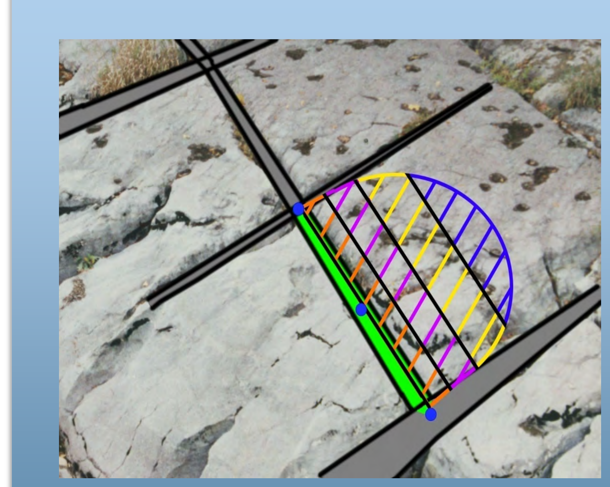
$$Q = -\frac{hb^3}{12}\frac{\rho}{\mu}\frac{dP}{ds}$$

Segment Mid-points

- All interchange between flow paths and adjoining matrix rock is calculated at this point
- Does not need Matrix inverse to get Pseudo-Potential
- Possible to use linear algebra to eliminate these points during the solution process

$$\frac{hb}{RT}\frac{d}{dt}\int_{I-E}\frac{P}{Z}\,dl = Q_{I-e} + Q_{e-E} + Q_R^{RC} + Q_L^{RC}$$

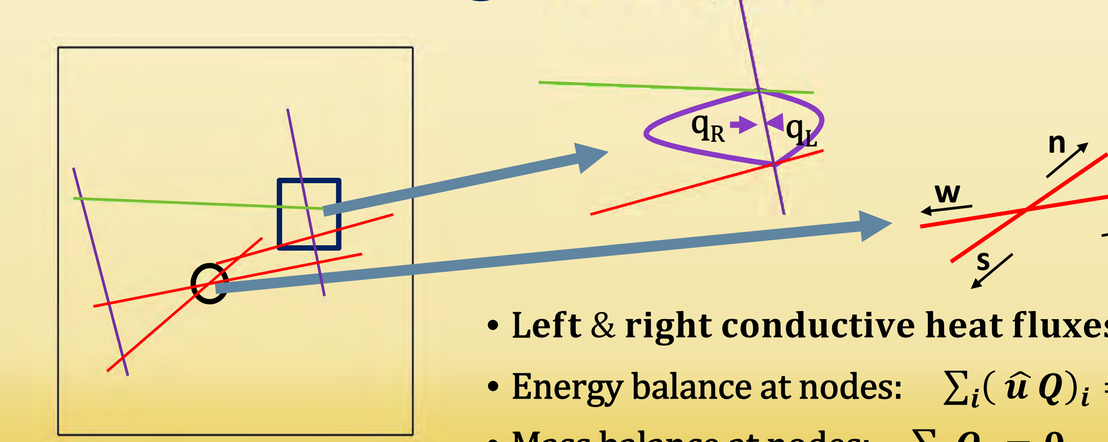
The Model



- Solve for Pseudo-Potentials rather than pressure to reduce non-linearity of the mass balance problem
- Newton-Raphson method used on Non-linear discrete problem
- Linear problem solved for using Thomas algorithm for matrix solution, SOR for flow path intersection

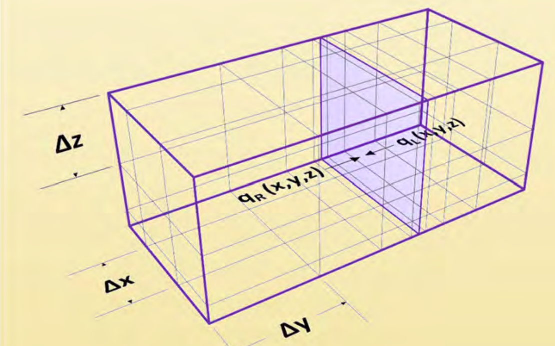
$$\Phi(P) = \int_0^P \frac{f(P')}{\mu(P')}dP'$$

Fracture Segments, Nodes, & Matrix Volumes



- Left & right conductive heat fluxes: q_L & $q_R = q_{L/R} = -k_r \frac{\partial\theta}{\partial y}\Big|_{L/R}$
- Energy balance at nodes: $\sum_i(\hat{u}\,Q)_i = 0\,,\ \ i = w, e, s, n, d, u$
- Mass balance at nodes: $\sum_i Q_i = 0\,,\ \ i = w, e, s, n, d, u$

Matrix to Fracture Flows as Discretized

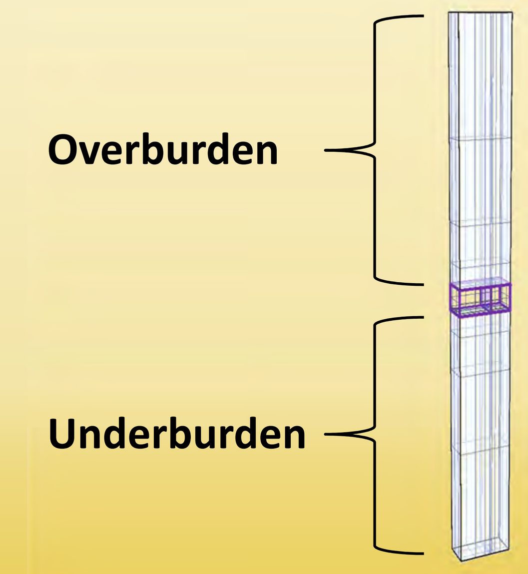


- Mass flux according to Darcy's Law: $\rho\vec{v} = -k_f\frac{\rho}{\mu}[\vec{\nabla}P + \rho\vec{g}]$
- Mass balance is derived from the continuity equation using the above expression for the mass flux: $\frac{\partial\rho}{\partial t} = -\vec{\nabla}\cdot\frac{k_f}{\mu}\{\rho[\vec{\nabla}P + \rho\vec{g}]\}$
- Pseudopotential: $\Phi = \int_0^P \frac{f(P',T)}{\mu(P',T)}\,dP'$, where

$$f_{gas} = \frac{P'}{T\,Z(P',T)} \ \ or\ \ f_{liquid} = \frac{\rho(P',T)}{\rho_{reference}}$$

- The mass flux is evaluated at the cell boundary using the pseudopotential and uses the boundary temperature: $\frac{\rho}{\mu}\nabla P \propto \nabla\Phi \longrightarrow \frac{\Delta\Phi(P,T_b)}{\Delta s}$ where $\Delta\Phi(P,T_b) = \Phi(P_I,T_b) - \Phi(P_J,T_b)$ and where I and J are indices on either side of the boundary.
- The equations are solved sequentially with the mass fluxes first computed and then used in the advection equations, $\rho\frac{\partial\hat{u}}{\partial t} + \rho\vec{v}\cdot\vec{\nabla}\hat{u} = \frac{1}{b}(q_L - q_R)$

Entire Domain Communicates with Fracture



- Conductive Heat Transfer: $(\rho c_p)_{eff}\frac{\partial\theta}{\partial t} = k_r\nabla^2\theta$
- Previous one-dimensional problems have expanded to three-dimensional problems
- No longer possible to decompose and simplify the problem as previously

U.S. DEPARTMENT OF ENERGY

This technical effort was performed in support of the National Energy Technology Laboratory's ongoing research under the RES contract DE-FE0004000.

Science & Engineering To Power Our Future