MODELING OF FLUID AND HEAT FLOW IN FRACTURED GEOTHERMAL RESERVOIRS

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Introduction

In most geothermal reservoirs large-scale permeability is dominated by fractures, while most of the heat and fluid reserves are stored in the rock matrix. Early-time fluid production comes mostly from the readily accessible fracture volume, while reservoir behavior at later time depends upon the ease with which fluid and heat can be transferred from the rock matrix to the fractures. Methods for modeling flow in fractured porous media must be able to deal with this matrix-fracture exchange, the so-called "interporosity" flow.

This paper reviews recent work at Lawrence Berkeley Laboratory on numerical modeling of nonisothermal multiphase flow in fractured porous media. We also give a brief summary of simulation applications to problems in geothermal production and reinjection.

General-purpose Simulator MULKOM

Fluid flow in geothermal reservoirs is invariably nonisothermal, and it often involves both a liquid and a vapor phase. The flow processes in fractured media do not differ in any fundamental way from those in porous media; however, some special issues and difficulties arise from the presence of the small but highly active fracture volume. We have developed a general-purpose reservoir simulator "MULKOM", which implements special techniques for effectively dealing with nonisothermal multiphase flow in fractured media (Pruess, 1983, 1988). The basic governing equations solved by MULKOM describe mass and energy conservation for multicomponent fluids which in addition to water may contain non-condensible gas such as CO_2 and dissolved solids such as NaCl or SiO_2. Fluid flow is described with a multiphase extension of Darcy's law; in addition there can also be binary diffusion in the gas phase. Heat flow occurs by conduction and convection, the latter including sensible as well as latent heat effects. The description of thermodynamic conditions is based on the assumption of local thermodynamic equilibrium among all phases (liquid, vapor, solid). Fluid properties are represented by steam table equations for water, and by suitable empirical correlations for other constituents. Different components (H_2O, CO_2, SiO_2, ...) can be present in several phases, according to local phase equilibria or by way of kinetic rates. Special techniques are used to handle phase transitions. All thermophysical and hydrologic parameters (including porosity and permeability) which appear in the governing equations can be arbitrary (nonlinear and differentiable) functions of the primary thermodynamic variables.

For numerical simulation the continuous space and time variables must be discretized. In MULKOM space discretization is made directly from the integral form of the basic conservation equations, without converting them into partial differential equations. This "integral finite difference" method (Narasimhan and Witherspoon, 1976) avoids any reference to a global system of coordinates, and thus offers the advantage of being applicable to regular or irregular discretizations in one, two, or three dimensions. It also offers special advantages when implementing multiple-porosity techniques for fractured media (see below). Time is discretized fully implicitly as a first-order backward finite difference. This together with 100 % upstream weighting of flux terms at interfaces is necessary to achieve unconditional stability (Peaceman, 1977), and to avoid impractical time step limitations when simulating flow in fractured media. The discretization results in a set of strongly coupled nonlinear algebraic equations, which are solved completely simultaneously, using Newton-Raphson iteration. Time steps are automatically adjusted (increased or reduced) during a simulation, depending on the convergence of the iteration process. The linear equations arising at each iteration step are solved with a sparse version of LU-decomposition and backsubstitution (Duff, 1977).

The accuracy of MULKOM was tested by comparison with analytical solutions and results from laboratory experiments (Lam et al., 1988). The simulator has been used for basic studies in geothermal reservoir dynamics, and for detailed reservoir performance simulations of specific geothermal fields (natural state as well as exploitation). Special versions of MULKOM have also been used for problems in enhanced oil recovery, underground natural gas storage, groundwater contamination, and high-level nuclear waste isolation. A detailed user's guide is available for a version of MULKOM for nonisothermal two-phase two-component flow of water and air, known as "TOUGH" (Pruess, 1987). TOUGH was specifically designed for simulation of fluid and heat flows near high-level nuclear waste packages emplaced in partially saturated media; it is also applicable to geothermal problems involving pure water by simply setting air mass fraction to zero in the input file. (*)

Approaches for Simulating Flow in Fractured Media.

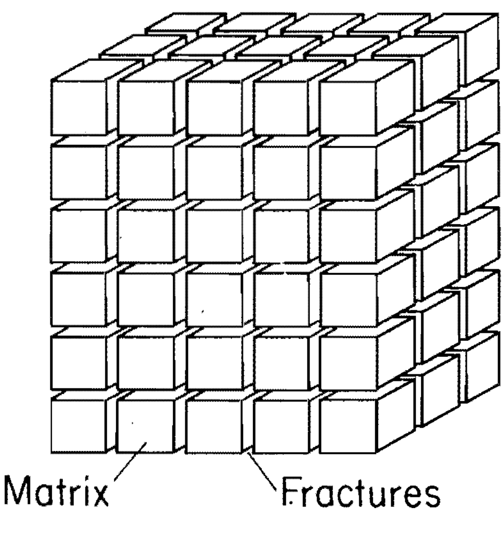
From a conceptual viewpoint the simplest approach for modeling flow in fractured media is to explicitly include fractures in the flow domain by means of suitably chosen small volume elements (grid blocks). Because of the amount of geometric detail involved in this approach, it can only deal with highly idealized problems with very few fractures

(*) TOUGH source code and documentation are available from the National Energy Software Center, c/o Argonne National Lab., 9700 South Cass Avenue, Argonne, Illinois 60439.

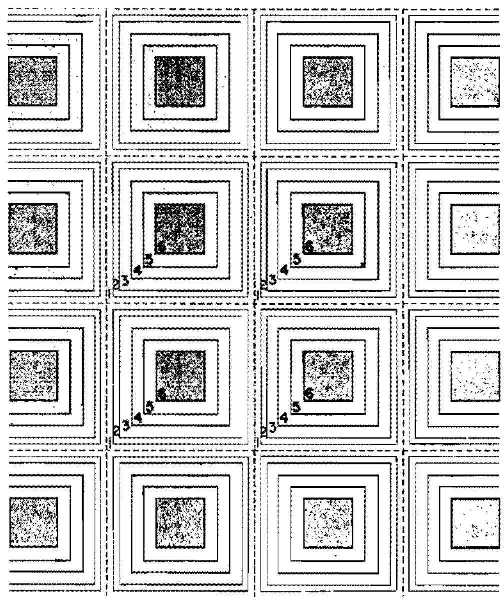
and a high degree of symmetry. At the opposite extreme compared to the "explicit fractures" approach is the "effective continuum" technique (Pruess et al., 1985). This approach involves the drastic simplification of not making any geometric representation of the fractures at all; instead their flow effects are approximated by means of suitably modified hydrologic parameters, chiefly relative permeability curves. Thereby the numerical problem is reduced to that of a porous medium model; however, such a "porous medium" or "effective continuum" approximation can only be justified when matrix and fractures remain in approximate thermodynamic equilibrium locally at all times (Pruess et al., 1988).

For geothermal reservoirs with spacing between major fractures often as large as several tens of meters, the thermodynamic equilibration between matrix and fractures in response to changing conditions in the fractures (caused by fluid withdrawal or nonisothermal reinjection) is a slow process. Indeed, thermal diffusivity of rocks is typically of the order of 10^{-6} m^2/s, so that a 30 m deep penetration of conductive effects into matrix blocks will require approximately 30 years. As far as fluid flow is concerned the permeability contrast between fractures and matrix is typically of the order of 10^4 (10 millidarcy versus 1 microdarcy); the corresponding diffusivity contrast is even larger because of small fracture porosity. Thus, reservoir perturbations induced by production or injection operations will propagate through the fracture system typically more than 100 times faster than through the rock matrix. These considerations indicate that one should expect persistent nonequilibrium conditions between matrix and fractures in many fractured geothermal reservoirs during exploitation. An effective continuum approximation should be applicable only when fracture spacing is "sufficiently" small. For conductive equilibration with impermeable blocks to occur within a few months, fracture spacing must be less than 2 - 3 m. If one wishes to resolve changes in reservoir conditions on a spatial scale of 50 m, say, then an effective continuum approximation should be applicable only when fracture spacing is less than 1 m. These numbers are meant to give an order-of-magnitude estimate for the fracture spacing required to justify application of the effective continuum approach.

Persistent nonequilibrium conditions between matrix and fractures, and the accompanying transient interporosity flow effects can be modeled with the method of "multiple interacting continua" (MINC; Pruess and Narasimhan, 1982, 1985). An extension of the well known double-porosity method (see Figure 1; Barenblatt et al., 1960; Warren and Root, 1963), the MINC method combines features of both the explicit fracture and effective continuum approaches. The fracture system is modeled as a continuum, which interacts with several matrix continua. The latter are defined based on the following consideration. Due to vastly different diffusivities, exploitation-induced perturbations in thermodynamic conditions in a fractured reservoir will propagate rapidly through the network of interconnected fractures, while invading the matrix blocks only slowly. Responding to the changing conditions in the fractures, the thermodynamic conditions in the matrix blocks will then change in a way that is primarily controlled by the distance to the nearest fracture. This concept leads to a discretization of matrix blocks into a series of nested volume elements, as schematically shown in Figure 2. Flow in this system can easily be modeled by means of the integral finite difference



1. Idealized double porosity model of a fractured porous medium.



2. Basic space discretization in the method of "multiple interacting continua" (MINC; after Pruess and Narasimhan, 1982).

technique, which only requires specification of grid block volumes, interface areas, and nodal distances (Pruess, 1983). The concept of discretizing matrix blocks according to distance from the nearest fracture can also be applied to irregular and stochastic fracture distributions (Pruess and Karasaki, 1983). If only two continua (one for the fractures, one for the matrix) are specified, the MINC method reduces to the double-porosity approach.

The accuracy of the MINC method has been demonstrated by comparison with analytical solutions (Lai et al., 1986), with explicit fracture calculations (Wu and Pruess, 1988), and with laboratory experiments (Lam et al., 1988). We have recently developed a simplification of the MINC method that is applicable to the problem of heat exchange with impermeable matrix blocks (Pruess and Wu, 1988). The simplification obviates the need for subgridding of matrix blocks; instead, temperature in the blocks is represented by means of a simple trial function, as follows:

$$T(x,t) - T_i = (T_f - T_i + px + qx^2)\exp(-x/d) \tag{1}$$

Here x is the distance from the block surface, T_i is initial block temperature, T_f is the time-varying temperature in the fractures (at the block surface), p and q are time-varying fit parameters, and d is the penetration depth for heat conduction, given by $d = \sqrt{(Dt)}/2$, where D is the thermal diffusivity of the blocks. The parameters p and q are calculated at each time step of a simulation run from requirements of energy conservation in the blocks, and continuity of heat flux at the block surface. This semi-analytical approach to interporosity flow can give accurate results with no noticeable increase in computational effort compared to simple porous medium models. An extension to permeable matrix blocks appears feasible and is currently under development.

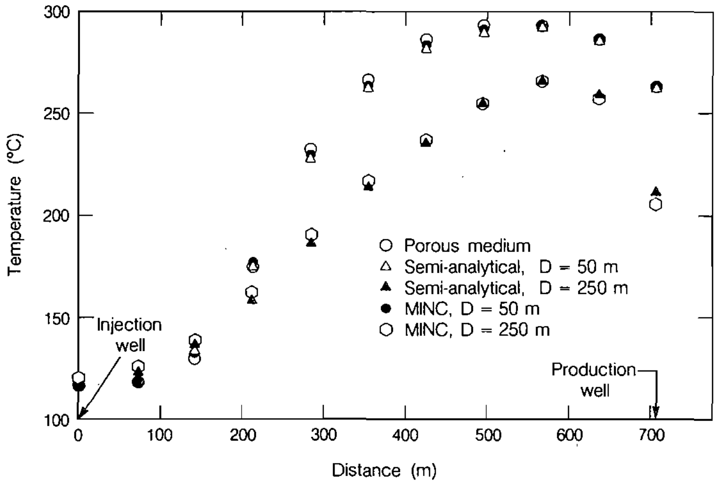
Applications

The special techniques developed for simulating fluid and heat flow in fractured porous media have been applied to modeling of laboratory experiments (Lam et al., 1988) and to fundamental studies of fractured geothermal reservoirs (see below). No applications to specific field case studies have been made yet, for several reasons. The few published simulation studies of fractured reservoirs (see the review by Bodvarsson et al., 1986) all utilized a porous medium model, even though the validity of an effective continuum approximation was never demonstrated and is in fact questionable. This approach was taken in the spirit of establishing a simple baseline (porous medium) case for reference, and to examine how far the simplest approach could go in replicating observed field behavior. In order to match well performance data (rates, enthalpies) at the Krafla/Iceland and Olkaria/Kenya geothermal fields, rather small values for reservoir porosity of the order of 0.5 - 4 % had to be used (Pruess et al., 1984; Bodvarsson et al., 1987). We interpret these small porosities as representing the easily accessible pore space, mostly in the fractures, which is expected to dominate earlier-time well behavior. The less accessible matrix volume should influence the longer-term reservoir response to exploitation, so that shortcomings of the porous medium models should eventually become apparent. Application of the MINC-approach to field simulations should pose no particular problems. This will however require more detailed data on fracture distributions and fracture and matrix permeabilities and porosities. Computational work compared to porous medium models is expected to increase by typically a factor of five.

Reservoir Dynamics

Applications of the MINC method have produced valuable insights into fluid and heat flow conditions in fractured boiling reservoirs. For example, a mechanism of conductive enhancement of flowing enthalpy was discovered which will cause superheated steam to be discharged from matrix blocks of low permeability, even if liquid saturation in the matrix blocks is large (Pruess and Narasimhan, 1982; Pruess, 1983). Possible mechanisms for natural evolution of two-phase liquid and vapor dominated systems were demonstrated (Pruess, 1985; Pruess et al., 1987). The presence of non-condensible gases was shown to give rise to some unsual effects in fractured media (Pruess et al., 1985; Bodvarsson and Gaulke, 1987).

Of particular interest in fractured reservoirs is their response to reinjection of heat-depleted waste waters. This could result in enhanced energy recovery, but it also raises the possibility of premature thermal breakthrough of reinjected waters along preferential pathways (major fractures or faults). Tracer tests can reveal such short-circuiting paths, but there is no general quantitatively useful relationship between breakthrough of tracer fronts and thermal fronts. Simulation studies have suggested that thermal degradation at production wells should be largely reversible if the offending injector is shut in (Pruess and Bodvarsson, 1984). Injection studies in fractured two-phase and vapor zones have shown interesting fluid and heat flow phenomena (Pruess, 1983; Pruess and Narasimhan, 1985; Bodvarsson et al., 1985; Calore et al., 1986). In a five-spot production-injection problem it was found that for 50 m fracture spacing a nearly complete heat sweep could be achieved, while for 250 m fracture spacing significant heat reserves were bypassed. This can be seen from Figure 3, which shows the simulated temperature profile in the fractures along a line connecting production and injection wells after 36.5 years of constant-rate production and 100 % reinjection (Pruess and Wu, 1988). The data for 50 m fracture spacing virtually coincide with a porous medium model, indicating excellent thermal sweep, while those for 250 m fracture spacing indicate substantial bypassing. Figure 3 also shows excellent agreement between results obtained from the semi-analytical method for interporosity flow and the MINC method.



3. Simulated temperature profiles in five-spot production-injection system for different fracture spacings after 36.5 years (after Pruess and Wu, 1988).

Discussion and Conclusions

Fluid and heat flow in fractured geothermal reservoirs involves complex phenomena operating on different space and time scales. From a modeling point of view these phenomena are characterized by highly nonlinear mathematical relationships. Flexible and robust simulation techniques are now available for fundamental studies as well as for field applications. These techniques have already given much new insight into the dynamical behavior of fractured reservoirs, and their response to production and injection operations.

Practical applications have been limited by difficulties to adequately characterize fractured reservoirs over a wide range of spatial scales. Some challenging research problems exist in the characterization and modeling of fundamental processes. Important effects such as porosity and permeability change from variations in pore pressures and rock stresses, and from chemical dissolution and precipitation of minerals, have not yet been adequately explored. There also is a lack of data on multiphase flow characteristics (relative permeabilities and capillary pressures) of "real" rough-walled fractures. If available, such data could substantially enhance the reliability and usefulness of numerical simulation predictions.

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