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Improved Dual-Porosity Models for Geothermal Reservoir Simulation

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Since their introduction by Barenblatt et al. (1960), dual-porosity models have been widely used for simulating flow in fractured reservoirs. In a dual-porosity system, the matrix blocks provide most of the storage of the reservoir, whereas the fractures provide the global transmissivity. Initially, most work on dual-porosity models emphasized the development of analytical solutions for idealized reservoir problems. Increasingly, the dual-porosity approach is being implemented by numerical reservoir simulators. Accurate numerical simulation of a dual-porosity problem often requires a prohibitively large number of computational cells to resolve the transient pressure or saturation gradients in the matrix blocks. As part of our DOE-funded research on improved methods for geothermal reservoir simulation, we have been developing procedures for dual-porosity reservoir simulation that circumvent the need to discretize the matrix blocks. In our new approach, the mass and energy interactions between the fractures and matrix blocks are described by nonlinear ordinary differential equations. When implemented into a numerical simulator, this procedure eliminates the need to discretize the matrix blocks and thereby allows more efficient simulation of reservoir problems. This approach has been carried out for single-phase isothermal flow (Zimmerman et al., 1993a) and single-phase nonisothermal flow (Zimmerman et al., 1993b); it is currently being extended to two-phase (water/steam) flow of the type that occurs in geothermal reservoirs. In the following summary, we describe the application of this method to single-phase isothermal flow problems.

DUAL-POROSITY MODELS

When a single-phase, slightly compressible fluid flows isothermally through a macroscopically homogeneous fractured medium, the fluid pressure P_f in the fractures is governed by the equation

$$\phi_f c_f \frac{\partial P_f(x,t)}{\partial t} = \frac{k_f}{\mu} \nabla^2 P_f(x,t) + Q(x,t) \ , \qquad (1)$$

where t is time, x is the position vector of a point in the fracture continuum, k_f is the effective permeability of the fracture continuum, ϕ_f is the total fracture porosity, and c_f is the total compressibility of the fractures and the fluid within them. Q is a volumetric source/sink term representing fluid flow from the matrix blocks to the fracture system per unit of total volume.

One commonly used type of dual-porosity model allows global flow only through the fracture network, with the matrix blocks serving as continuously distributed sources/sinks of fluid for the fractures. The matrix blocks at each location in the fracture continuum are represented by a single average pressure, $P_m(x,t)$. Conservation of mass for the matrix block leads to the following equation for P_m:

$$\phi_m c_m \frac{\partial P_m(x,t)}{\partial t} = -Q(x,t) \ . \qquad (2)$$

To close the system of equations given by (1) and (2), an equation is needed to relate Q to P_f and P_m. Warren and Root (1963) assumed that Q is proportional to $P_f - P_m$:

$$Q(x,t) = -\frac{\alpha k_m}{\mu}\left(P_f - P_m\right) \ , \qquad (3)$$

where α has dimensions of 1/area. Equation (3) is often referred to as the "quasi-steady-state" approximation (Chen, 1989). This terminology follows from consideration of the problem in which there is an instantaneous change in the fracture pressure P_f, which serves as the boundary condition for the matrix block, which we assume here to be a sphere of radius a_m. Differentiation of the most-slowly-decaying Fourier component in the expression for the average pressure, which is the dominant component at large times, leads to an equation of the same form as Eqs. (2) and (3), with $\alpha = \pi^2 / a_m^2$. Other matrix block shapes, such as slabs or cubes, lead to long-time behavior governed by similar equations, but with different expressions for α (see Zimmerman et al., 1993a).

NONLINEAR COUPLING EQUATION

An exact coupling term could be developed in terms of the step-function response of a single spherical matrix block by using the convolution principle. This would then require the calculation of convolution integrals for each fracture gridblock at each time step and would also require the storage of past values of the matrix pressure. Pruess and Wu (1989) and Dykhuizen (1990) improved upon the quasi-steady-state model by approximating flow in the matrix blocks with trial functions that satisfy the boundary conditions and global mass conservation. We have taken

the somewhat different approach of utilizing a nonlinear ordinary differential equation that, in some sense, approximates the linear partial differential equation that actually governs P_m. This equation, first proposed by Vermeulen (1953) in the context of ion-exchange chromatography, is:

$$\phi_m c_m \frac{\partial P_m}{\partial t} = \frac{\pi^2 k_m}{2\mu a_m^2} \frac{\left(P_f - P_i\right)^2 - \left(P_m - P_i\right)^2}{P_m - P_i} , \qquad (4)$$

where P_i is the initial pressure. When P_m is close to P_f, Eq. (4) reduces to Eq. (3) and is therefore accurate in the long-time regime. We have also proved that Eq. (4) is very accurate in the small-time limit for arbitrary fracture-pressure variations $P_f(t)$ (Zimmerman et al., 1993a).

Equation (4) has been tested under situations in which the fracture pressure, which serves as the boundary condition for the matrix block, is a known function of time, thereby isolating the matrix pressure response from that of the overall reservoir. Figure 1 shows the mean matrix block pressure for the case when the fracture pressure increases abruptly from P_i to P_0 at $t = 0$. The solution to Eq. (4) in this case very closely approximates the exact solution, whereas the prediction of the Warren-Root method, Eqs. (2) and (3), is not accurate until the process is nearly complete. The nonlinear Eq. (4) was also found to be more accurate than the Warren-Root method for ramp-function and other types of boundary conditions (Zimmerman et al., 1993a).

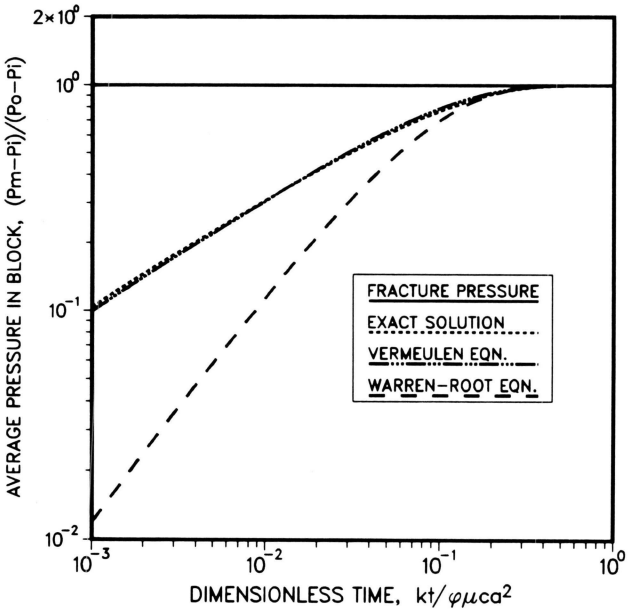

Figure 1. Average matrix pressure in a spherical block that is subjected to a step-function increase in pressure at its outer boundary. [XBL 927-1550]

DUAL-POROSITY SIMULATIONS

After verifying that Eq. (4) accurately predicts the mean matrix pressure under a wide variety of boundary conditions, we then incorporated it into the simulator TOUGH (Pruess, 1987) as a fracture/matrix coupling term. In this modification to TOUGH, Eqs. (2) and (4) are used in each fracture gridblock and at each time step to calculate the mass interaction term Q. The solution to the first-order ordinary differential equation (4) is carried out in a fully implicit manner, so as to be consistent with TOUGH and to avoid numerical instabilities. When performing reservoir simulations with this modified version of TOUGH, each computational gridblock represents an element of the fracture continuum, with the fracture/matrix flow interaction computed from Eqs. (2) and (4). We have verified the accuracy of this new approach by comparing its predictions against those of a MINC-type simulation (Pruess and Narasimhan, 1985), in which the matrix blocks are represented by nested concentric gridblocks. As an example of the use of the new method, consider flow from a boundary that is maintained at a constant pressure P_0, into a semi-infinite fractured formation that is initially at pressure P_i. The permeabilities are taken as $k_f = 10^{-15}$ m^2 and $k_m = 10^{-18}$ m^2, the porosities as $\phi_f = 0.001$ and $\phi_m = 0.1$, and the matrix block radii as $a_m = 1$ m. The temperature is 20°C, and the boundary and initial pressures are $P_i = 10$ MPa and $P_0 = 11$ MPa.

The flow rate into the formation is shown in Figure 2. In the case labeled "MINC-1 shell," each matrix block was represented by a single computational cell; this is a numerical implementation of the Warren-Root equation (3). In the case labeled "MINC-10 shells," each matrix block was discretized into 10 concentric shells. All three computations predict the correct pressure response in the short- and long-time limits, when $P_f \approx t^{-1/2}$. In the intermediate-time regime, when the matrix blocks near the inlet are being filled, the Warren-Root method incorrectly predicts $P_f \approx$ constant, whereas the new method correctly leads to the known (Nitao and Buscheck, 1991) $t^{-1/4}$ pressure dependence. The MINC solution becomes more accurate as the number of shells increases and eventually approaches the solution obtained using our new method. The agreement with the finely gridded MINC solution serves to validate the new method.

The computational time required for simulating a given problem with a code such as TOUGH grows linearly with the number of computational cells, since most of the computing effort consists in inverting a sparse matrix by Gaussian elimination. Since the nonlinear coupling equation removes the need for discretizing the matrix blocks, the number of computational gridblocks can be decreased by about a factor of N, where N is the number of MINC shells used in each gridblock. This would be expected to lead to a proportional decrease in CPU time. For example, in the simulations shown in Figure 2, 14 fracture gridblocks and 1 boundary gridblock were used to simulate flow into the

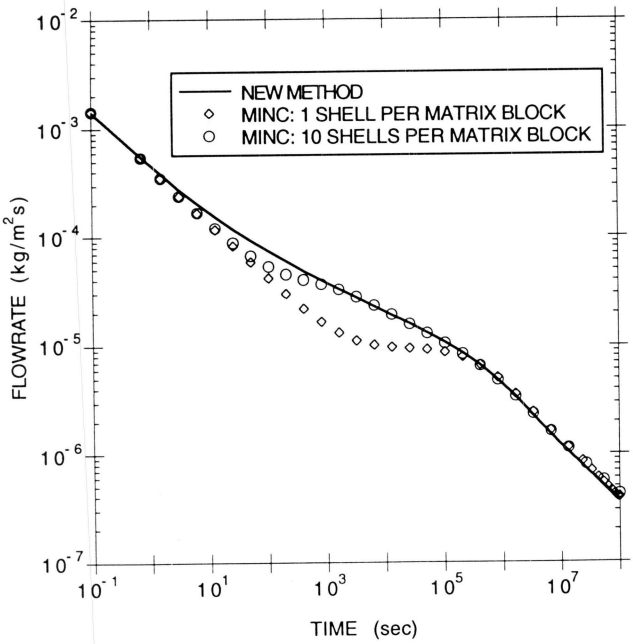

Figure 2. Flow rate into one-dimensional fractured formation under constant-pressure boundary conditions. Matrix and fracture properties are as described in text. [XBL 936-884]

semi-infinite formation when using the new method. The MINC-10 shell simulation therefore used 155 computational elements: 1 boundary element, 14 fracture elements, and $14 \times 10 = 140$ matrix elements. The decrease in the number of computational elements afforded by the new method was therefore 90%, and the savings in CPU time was in fact 88%. The slight difference is probably due to the small amount of computational work needed to solve Eq. (4).

DISCUSSION

The method described above for modeling the flow of a single-phase fluid between a matrix block and the surrounding fractures can also be used to model heat conduction, since both processes are governed by the diffusion equation. This analogy was pointed out by Pruess and Wu (1989), who used the integral-method approach to model both phenomena. We have extended our nonlinear coupling equation approach to heat conduction (Zimmerman et al., 1993b) and also to two-phase processes in which the liquid is immobile (Zimmerman, et al., 1993b). In the latter case, the fluid flow can be modeled by a single diffusion equation by introducing a "pseudo-compressibility" for the two-phase mixture (Grant and Sorey, 1979). We are currently working on extending this approach to two-phase flow processes in which both phases are mobile.

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