Particle-based Simulation of Hydraulic Fracture and Fluid/Heat Flow in Geothermal Reservoirs

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Abstract. Realizing the potential of geothermal energy as a cheap, green, sustainable resource to provide for the planet's future energy demands that a key geophysical problem be solved first: how to develop and maintain a network of multiple fluid flow pathways for the time required to deplete the heat within a given region. We present the key components for micro-scale particle-based numerical modeling of hydraulic fracture, and fluid and heat flow in geothermal reservoirs. They are based on the latest developments of ESyS-Particle – the coupling of the Lattice Solid Model (LSM) to simulate the nonlinear dynamics of complex solids with the Lattice Boltzmann Method (LBM) applied to the nonlinear dynamics of coupled fluid and heat flow in the complex solid–fluid system. The coupled LSM/LBM can be used to simulate development of fracture systems in discontinuous media, elastic stress release, fluid injection and the consequent slip at joint surfaces, and hydraulic fracturing; heat exchange between hot rocks and water within flow pathways created through hydraulic fracturing; and fluid flow through complex, narrow, compact and gouge- or powder-filled fracture and joint systems. We demonstrate the coupled LSM/LBM to simulate the fundamental processes listed above, which are all components for the generation and sustainability of the hot-fractured rock geothermal energy fracture systems required to exploit this new green-energy resource.

Keywords: Lattice Boltzmann particle-fluid interaction, geothermal energy, coupled Lattice Solid/Lattice Boltzmann Model, Discrete Element Method, Lattice Solid Model.
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INTRODUCTION

In the coming years, modeling of hydraulic fracture and flow of fluid and heat in fragmented material will play a vital role in the exploitation of geothermal energy. Deep geothermal energy extraction involves drilling boreholes into hot rocks and injecting water under high pressure, which decreases the effective friction on closed (impermeable) inter-meshing joint surfaces and causes them to "fracture" and slip in response to local tectonic pre-stress. The fracture and slip of these joints creates high permeability pathways for fluid flow. Thermal energy trapped in the rocks can then be extracted by circulating water between the injection and production wells through this permeable fracture system. Costs and the difficulty of accessing underground wells bring huge risks and uncertainties. Challenges in geothermal energy extraction include how to stimulate and sustain the flow of water through the geothermal field, and how to generate an efficient hydraulic subsurface heat exchange (fracture) system.

A fully developed thermo-hydro-mechanical coupling model and code that includes the most important physical mechanisms would enable study of the phenomena and meet this challenge with minimal cost and risk. Many approaches have been proposed for simulating fragmentation of solids using continuum-based models; but while these can simulate discontinuities to an extent (either replacing the discontinuities with material of a different rheology, or through special treatments of the discontinuity nodes), they cannot be used to study emergent behavior or probe the evolution of fracture systems (a consequence of microscopic processes). Particle-based models such as the Discrete Element Method (DEM) and Lattice Solid Model (LSM) naturally overcome such difficulties, since displacements and detachment of solid fragments can be simulated.

For fluids, the classical continuum approach incorporates computational fluid dynamics, with numerical solution of Navier-Stokes (NS) equations. But as with solids, there are alternative microscopic and mesoscopic approaches, such as the Molecular Dynamics method (MD), Smoothed Particle Hydrodynamics, and the Lattice Boltzmann Method (LBM). A semi-microscopic approach, LBM is based on the kinetic gas theory, and simulates fluid flows by tracking the evolving distributions of particles rather than individual particles. Advantages include ease of implementation and parallelization, and ability to handle boundary conditions of complicated geometries [2]

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We introduce a microscopic model coupling the LSM and LBM to allow simulations of solid–fluid coupling, fracture, and thermal fluid flow, and to explore the creation, evolution, and efficiency of geothermal reservoir fracture systems as emergent phenomena.

Overview of the Lattice Solid Model

The Lattice Solid Model simulates the dynamics of a system of interacting particles and was originally motivated by MD [6]. However, whereas the MD method is microscopic and simulates atoms or molecules via the inter-atomic or inter-molecular potential function, the LSM is mesoscopic and simulates groups of atoms or "grains" interacting at a meso-scale (e.g. irreversible brittle fracture for bonded grains under tension, bending, and torsion, and friction of unbonded grains according a prescribed relation such as based on a theoretical model (e.g. Coulomb friction) or as derived in lab studies. In the macroscopic limit, one can show that the emergent behavior of a bonded Lattice Solid Model is that of an elastic solid [7-11] and numerous numerical studies have demonstrated that realistic fracturing behavior can be simulated. The LSM model is able to simulate heat flow and Darcy fluid flow through the evolving solid lattice [1] and has been applied to numerous studies aimed at understanding the nonlinear dynamics and forecastability of earthquakes [7-10]

The Thermal Lattice Boltzmann Method

We use the thermal-energy-distribution type BGK thermal Lattice Boltzmann Method [3,4,5], which has been shown to yield the NS equations for fluid flow combined with heat flow. Namely, in one time step Δt, the mass density of particles that move in the α - direction of a regular lattice moving with velocity $\mathbf{c}_\alpha$ denoted f_α is updated as

$$f_\alpha(\mathbf{x}, t+\Delta t) = f_\alpha(\mathbf{x}-\Delta\mathbf{x}_\alpha, t) + \Delta f_\alpha^C(\mathbf{x}, t+\Delta t)/\tau_f,$$

where the first term on the right denotes the streaming of particles moving one lattice spacing $\Delta\mathbf{x}_\alpha$ in the α - direction in one time step, and the second term on the right denotes the redistribution of mass density flow due to collisions where τ_f is the dimensionless relaxation time constant for the collision term – related to kinematic viscosity via $\nu_f = (\tau_f - 0.5)c_s^2\Delta t$, where c_s is the speed of sound in the fluid. The collision term is calculated using

$$\Delta f_\alpha^C = f_{eq}^\alpha - f^\alpha .$$

In this work, we model the 2D case of a square lattice using 9 particle velocities (i.e. the D2Q9 BGK model) so the particle distributions travel with speeds of $c_\alpha = 0, (\alpha = 0)$, $c_\alpha = \Delta x/\Delta t, (\alpha = 1,2,3,4)$ particles moving in the $\pm x$ and $\pm y$ directions and $c_\alpha = \sqrt{2}\Delta x/\Delta t \quad (\alpha = 5,6,7,8)$ for particles traveling in the diagonal directions. The equilibrium distribution is calculated using

$$f_\alpha^{eq} = \rho w_\alpha [1 + 3\mathbf{c}_\alpha\cdot\mathbf{u} + \tfrac{9}{2}(\mathbf{c}_\alpha\cdot\mathbf{u})^2 - \tfrac{3}{2}\mathbf{u}\cdot\mathbf{u}],$$

where the equilibrium distribution weights are $w_\alpha = (4/9, 1/9, 1/9, 1/9, 1/9, 1/36, 1/36, 1/36, 1/36)$. For this case, the RMS velocity, and hence the speed of sound in the fluid is $c_s = 1/\sqrt{3}$. The macroscopic density and momentum are calculated using $\rho = \sum_\alpha f_\alpha$ and $\rho\mathbf{u} = \sum_\alpha f_\alpha \mathbf{c}_\alpha$. In the thermal Lattice Boltzmann Method, a second distribution g_α is introduced which relates to kinetic energy within the fluid and hence to heat. This is also modeled in the two steps of streaming and collision

$$g_\alpha(\mathbf{x}, t+\Delta t) = g_\alpha(\mathbf{x}-\Delta\mathbf{x}_\alpha, t) + \Delta g_\alpha^C(\mathbf{x}, t+\Delta t)/\tau_g,$$

where collision term is $\Delta g_\alpha^C = g_{eq}^\alpha - g^\alpha$ and the equilibrium distribution for g_α is calculated using

$$g_\alpha^{eq} = \tfrac{1}{2}\rho(\mathbf{c}_\alpha - \mathbf{u})^2 w_\alpha [1 + 3\mathbf{c}_\alpha\cdot\mathbf{u} + \tfrac{9}{2}(\mathbf{c}_\alpha\cdot\mathbf{u})^2 - \tfrac{3}{2}\mathbf{u}\cdot\mathbf{u}].$$

The macroscopic internal kinetic energy and temperature are calculated using $\rho E = \sum_\alpha g_\alpha$ and $E = DRT/2$, where $D = 2$ is the number of dimensions, R is the gas constant, and T is the temperature. In the above equations, the different relaxation time τ_g allows the thermal diffusivity of the fluid to be controlled.

Mechanical Coupling of the Lattice Solid Model and Lattice Boltzmann Method

To implement mechanical coupling between the LSM and LBM, the following issues need to be considered: moving boundary conditions for a curved solid–fluid interface; momentum transfer between solid particles and the fluid; and force transfer between fluid nodes and solid particles. Here Yu's moving boundary condition is adopted [12]

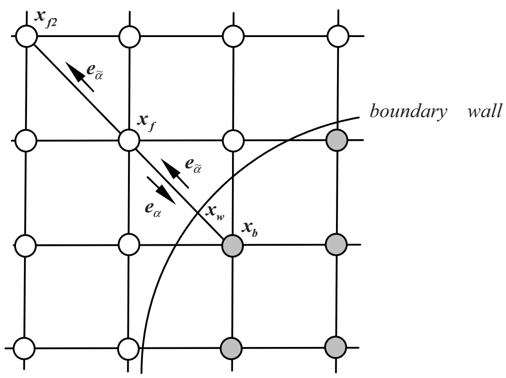

FIGURE 1. The moving curved wall boundary condition.

The lattice nodes are $\boldsymbol{x}_f$ (fluid side of the boundary; see Fig. 1) and $\boldsymbol{x}_b$ (solid side). The particle momentum moving from $\boldsymbol{x}_f$ to $\boldsymbol{x}_b$ is $\boldsymbol{e}_\alpha$, and the revised momentum from $\boldsymbol{x}_b$ to $\boldsymbol{x}_f$ is $\boldsymbol{e}_{\tilde{\alpha}} = -\boldsymbol{e}_\alpha$. Here, $\boldsymbol{x}_w$ denotes the intersection of the wall with the lattice link. Due to the arbitrary position of the particles and the curved particle surface, the particle surface can intersect the link between two nodes at an arbitrary distance.

To capture the position of the particle surface accurately, the fraction of an intersected link in the fluid region can be computed as

$$\delta = \frac{|\boldsymbol{x}_f - \boldsymbol{x}_w|}{|\boldsymbol{x}_f - \boldsymbol{x}_b|} \in (0,1] \cdot$$

The reflected distribution function at nodes can be calculated using an interpolation scheme:

$$f_{\tilde{\alpha}}(\boldsymbol{x}_f, t+\Delta t) = \frac{1}{1+\delta}\Big[(1-\delta)\cdot f_\alpha(\boldsymbol{x}_f, t+\Delta t) + \delta \cdot f_\alpha(\boldsymbol{x}_b, t+\Delta t) + \delta \cdot f_{\tilde{\alpha}}(\boldsymbol{x}_{f2}, t+\Delta t) - 6 w_\alpha \rho_w \boldsymbol{e}_\alpha \cdot \boldsymbol{u}_w / c^2\Big].$$

The fluid force acting on the particle surface (added to the particle force in LSM code) can be obtained using

$$\boldsymbol{f}_F = \sum_{x_b}\sum_{\alpha=1}^{9} \boldsymbol{e}_\alpha\left[f_\alpha(\boldsymbol{x}_b, t) + f_{\tilde{\alpha}}(\boldsymbol{x}_f, t+\Delta t)\right]\Delta \boldsymbol{x}/\Delta t \ .$$

The first summation is over all fluid nodes adjacent to the particle at $\boldsymbol{x}_b$, and the second is over all possible lattice directions pointing toward a particle cell.

Thermal Coupling of the Lattice Solid Model and Lattice Boltzmann Method

The thermal coupling between the Lattice Solid Model and Lattice Boltzmann Method has the same issues as the mechanical coupling, and can be achieved in the same way. However, because the thermal diffusion time scale is longer than that of solid and fluid dynamical processes, it is less sensitive to the precision of the implementation. On the other hand, the thermal LBM can become unstable and care must be taken in the implementation, particularly when the fluid is undergoing rapid dynamical interaction with a solid, and hence may be far from equilibrium during such processes. We have implemented heat transfer within the Lattice Solid using the thermal LBM with a third distribution h_α, and a different relaxation time τ_h, which allows the solid to have a different thermal diffusivity than the fluid. This modeling of the heat flow in the moving lattice solid fragments (groups of bonded particles) consistently with the LBM leads to stable modeling of heat in the solid–fluid system, yielding relatively homogeneous numerical precision for the heat flow calculations within both solid and fluid regions. Different methods for solid and fluid regions would have yielded more heterogeneous precision.

Hydraulic Fracture Example

Fig. 2 shows a 2D simulation of hydraulic fracturing of rock, modeled as 1026 bonded LSM particles. Water is injected under pressure into a central hole (representing a borehole).

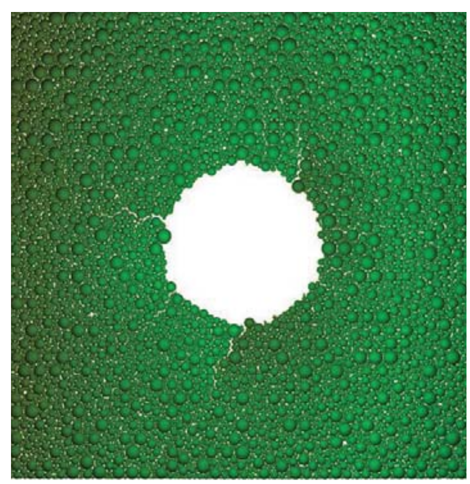

FIGURE 2. Snapshot of a simulation of hydraulic fracture.

Particle sizes range from 0.1 to 1 units. Water is simulated using the LBM. The minimum particle size is twice the LBM grid size of the fluid. Pressure in the center of the hole increases to model the slow injection of water, coded by addition of a source term on the right-hand side of the standard LBM scheme. Cracks start from the surface of the borehole and propagate in the rock due to the fluid pressure. Tensile fractures are dominant in the beginning of the crack initiation. Our simulations include most mechanisms of the hydraulic fracturing process: (i) mechanical deformation and fracturing induced by the fluid pressure; (ii) flow of fluid within the fracture; and (iii) fracture propagation.

Heat Flow Example: Cold Fluid Through Hot Rock

We digitized a 2D porous sandstone to generate the Lattice Solid lattice representing the rock. The digitized grains were shrunk to introduce permeability that would be present in 3D, and were then initialized with a uniform high temperature. Space between grains was filled with a cold fluid with a velocity $\mathbf{u} = (0.1c_s, 0)$. Left and right boundary conditions imposed continued flow to the right, and upper and lower boundaries were non-slip. Fig. 3 depicts a snapshot of the temperature and velocity fields at t = 700 time-steps of a simulation. The results illustrate the ability of the coupled Lattice Solid/Lattice Boltzmann Model to simulate combined fluid/heat flow within a complex solid–fluid system.

Conclusion

Examples in this paper show the potential of the coupled Lattice Solid/Lattice Boltzmann Model to simulate the creation, dynamics, evolution, and energy yield of realistic deep geothermal reservoir systems as emergent phenomena. Although the Discrete Element Method (DEM) and Lattice Boltzmann Method (LBM) have been available for 20–30 years, their combination is quite new. This is the first time the conjunction of DEM and LBM has been used to model geothermal energy extraction. Currently only 2D code is ready, and the simulations are still qualitative. Quantitative simulations will be possible after substantial work on parameter calibration and testing have been done. The 3D coupling code is still under development. The DEM code is already 3D, but 3D LBM code is different with that of 2D, and extra work is needed in this coupling.

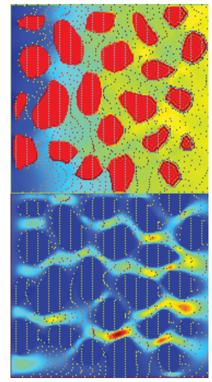

FIGURE 3. Temperature T (top) and fluid velocity magnitude $|\mathbf{u}|$ at $t = 700$ time steps in a simulation of an initially cold fluid with high thermal diffusivity, through a hot solid porous and permeable 2D sandstone matrix with low thermal diffusivity. Lines (they started as vertical columns) are tracer particles, allowing flow and temperature to be visualized simultaneously. Red = hot/fast, blue = cold/slow.

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