MODELLING HEAT TRANSFER AND ROCK DEFORMATION PROCESSES IN GEOTHERMAL SYSTEMS

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The geothermal research program at the University of Colorado encompasses three primary areas of study. These include:

1. Analysis and interpretation of data from the Mesa Anomaly. Development of a physically viable conceptual model of the undeveloped system.

2. Heat and mass transfer in simple models of liquid-dominated geothermal systems. Analysis of flow, temperature and pressure distribution.

3. Rock deformation processes associated with mechanical loading (earth tides, tectonics) and extraction and reinjection of liquids.

During the Second Workshop we will present results of studies on:

(1) Steady Nonlinear Convection on a Saturated Porous Medium with Large Temperature Variation.

(2) The Vertical Convection of Heated Liquid in a Fault Zone in the Geothermal Environment.

(3) The Enhancement of Microfracture Structure in Rocks.

Steady Nonlinear Convection in a Saturated Porous Medium with Large Temperature Variation

Potentially exploitable liquid-dominated geothermal basins must be highly permeable and supplied with heat from below. If the physical situation in these basins is such that significant fluid motion is present, then heat may be convected toward the surface such that high enthalpy liquid is available at relatively shallow depths.

In order to understand the different factors influencing convective motion in a geothermal basin, we consider a simplified model. Our system is a rectangular, homogeneous, isotropic, water-saturated porous medium with rigid boundaries. The vertical sides are insulated, while the upper horizontal boundary is isothermal at a temperature T_o and the lower horizontal boundary is isothermal at a higher temperature T_1. The density and viscosity of the water are functions of the temperature while all other properties are taken as temperature independent. For simplicity, we only consider two-dimensional convection.

The describing equations show that convection will start if the value of the Rayleigh number (R) of the system which is a measure of the ratio of the buoyancy force to the viscous resistance exceeds a critical value (R_c) which is a monotonic decreasing function of the temperature difference $\Delta T = T_1 - T_o$. In this case the amount of heat transfer increases significantly from its conduction value.

Because of the nonlinearity of the describing equations when convection is present, numerical solution of the equations is essential. However, when R is only slightly larger than R_c weakly nonlinear analysis is possible. A result of this analysis shows that the Nusselt number (Nu) which is the ratio of the heat transfer across the system to its conduction value is given approximately by $Nu \approx 1 + \frac{R(R - R_c)}{a+bR+cR^2}$ where a, b and c are functions of ΔT such that for a specific value of R the Nusselt number was found to increase as ΔT increases. These approximate results were used to check the numerical code for values of $R \rightarrow R_c^+$

The solution to the full initial boundary value problem which describes natural convection in the system was found by the finite difference method. The parabolic energy equation was solved by the alternating direction implicit method. The elliptic momentum equation was solved by the successive over relaxation method. An initial perturbation is assumed followed by marching in time until a steady state is reached. Estimates of accuracy were found by mesh size reduction.

Our numerical results were checked against published results for constant viscosity computations with good agreement. Excellent agreement with the weakly nonlinear theory was also found for values of $\frac{R}{R_c} \lesssim 1.2$. It was found that:

1. Although the Nusselt number increases with an increase of ΔT at the specified value of R, a universal curve is found to describe the variation of the Nusselt number with R/R_c for values of $0 < \Delta T \leq 200^oC$.

2. The velocity and temperature distributions are considerably influenced by the viscosity dependence on temperature. The horizontal motion is faster near the lower boundary. The ascending high temperature fluid is moving faster than the colder descending fluid.

3. Thermal boundary layers with strong temperature gradients are found to exist at increasingly smaller values of R/R_c as the temperature difference increases.

4. Temperature distributions with depth cannot always be used to delineate conduction and convection regions.

5. In the upflow section of the convection cell distortion of high temperature isotherms may lead to flashing at relatively shallow depths.

The Vertical Convection of Heated Liquid in a Fault Zone in the Geothermal Environment

There is abundant evidence in Long Valley, the Imperial Valley, the Coso area, Wairakei, Broadlands, and the Rio Grande Rift region among others, which suggests that fault zones are intimately associated with geothermal activity. In many of these areas thermal anomalies and hot springs are aligned with the faults themselves. This juxtaposition implied that the faults provide a path for convecting heated liquid from depth. When the rising hot water intersects a relatively permeable horizontal aquifer a charging process could occur leading to a reservoir of geothermal fluids. In this sense it seems reasonable to suggest that localized geological structure (faults and aquifers) controls the heat and mass transfer in geothermal systems rather than the large scale hydrodynamical convection patterns studied so frequently. With this in mind we have initiated a study of heat and mass transfer in models of a fault zone.

The fault zone is imagined to be a region of heavily fractured rock with a finite transverse dimension (as opposed to a single discrete crack) which extends for some indefinite length along the earth's surface. Microearthquake data suggests that these faults may descend to a depth far in excess of that associated with geothermal reservoirs (≥ 4 km). Thus it is assumed that the fault extends through a region of sedimentary material into the basement complex beneath. Due to periodic tectonic activity the fracture system in the fault zone is maintained. Thus the fault region, with a relatively high fracture permeability, can act as a localized conduit for the motion of fluid. In the most general model one imagines that surface water (precipitation, river runoff, etc.) percolates downward over a region of areal extent large compared to that of the fault. Although the general permeability may be insignificant with respect to that of the fault region, the large horizontal area involved permits significant quantities of liquid to reach the hot basement complex. Since the latter is thought to be heavily fractured, liquid from the periphery of the geothermal area can migrate through the hot rocks toward the fault zone. The driving mechanism for this lateral motion at depth is a pressure gradient associated with the difference between the hydrostatic pressure of the cold periphery fluid and that of the hot fluid at the same depth. Hence the fault can be charged with hot water which then rises upward in the channel composed of fractured material. At various horizons in the sedimentary section hot water may leave the fault to charge available aquifers. Should the fault extend to the surface, hot springs may appear.

In our first-order model we imagine a fault zone (extending to the surface) which intersects relatively impermeable sediments (no fluid loss). The zone is modelled as a narrow vertical slab of porous material. In the sedimentary section the walls, assumed to be impermeable, have a temperature that increases linearly with depth. Beneath the contact with the basement complex we assume that mass can pass through the walls which are at a constant high temperature. Two-dimensional solutions are sought for the flow configuration in the vertical slot (the fault as observed in the transverse dimension). Solutions are developed for the fault charging mechanism in the basement complex, for the region of initial cooling of liquid near the contact and the transition to fully-developed flow near the top of the fault. It is shown that the latter configurations can exist only if the fault zone Rayleigh number is sufficiently small. The analysis also indicates that two-dimensional solutions are possible only if a fault zone is sufficiently narrow, all other physical properties held fixed. For wider faults only three-dimensional flow configurations can exist. Such solutions are given for a limited range of Rayleigh numbers.

The Enhancement of Microfracture Structure in Rocks

A quantitative deterministic model of dilatancy (microfracture development) has been developed that fits the stress-strain relations for confining pressures between 0 and 4 kb. This includes loading, partial unloading and reloading. The description has been tested for rates of 10^{-5} to 10^{-6}/sec.

In connection with geothermal work, modelling is useful in two ways. First, dilatancy represents controllable porosity and this is obviously important to geothermal work. Changing the local stress fields may make it possible to induce a dilatant state with the associated greatly increased permeability. The other side of this is that improper pumping can decrease existing dilatancy. In either case a model is very useful.

Second, in the laboratory, dilatancy has been found to precede and control material failure. Pumping in a geothermal field can lead to dilatancy and failure with possible catastrophic effects on the field and the surroundings. This is not all bad in that a small earthquake may greatly increase fracturing.

The general approach adopted was statistical, based on the sliding grain boundary crack model. Slip on grain boundaries opens cracks that are parallel to the maximum principal stress axis and produces volumetric strain along the minimum compressive stress axis. Distribution functions f_s, f_σ, f_v for the boundary strength, local stress, and crack volume are required. These must depend on the stress invariants. This approach, as opposed to the more common continuum mechanics approach, is closely related to the micro-physics which makes it easier to interpret observations in terms of what is happening at individual cracks. Separating out the various dependencies simplifies the problem of including effects like chemical weakening. If it is known what the chemistry of the fluids does to the crack strength, then by modifying f_s accordingly the effect is included.

The stress invariants $Y = (3/4J_2')^{1/2}$ and $\overline{P} = P - 1/2(\frac{J_3'}{2})^{1/3}$ were chosen as the variables. Y is a measure of the maximum shear traction and $\overline{P}$ represents the average normal traction. As P increases, the frictional force that must be overcome by Y to cause sliding increases. The onset of dilatancy, $Y_D(\overline{P})$, is a measure of the weakest crack and the shape of this curve in $Y - \overline{P}$ space gives the effect of $\overline{P}$ on the failure stress, Y_s. The strength distribution f_s is required to give a cutoff at $Y_D(\overline{P})$. A convenient form, used to describe failure in ceramics, is $f_s(Y_s - Y_D(\overline{P})) = 2a(Y_s - Y_D)\exp(-a(Y - Y_D)2)$. Then the differential number of cracks opening is $dN(Y_s,\overline{P}) = f_s d(Y_s - Y_D)$. The stress distribution f_σ is taken to be a delta function for a first order theory. The form of the crack volume distribution f_V is unknown but assumed to be invariant, so that its effect can be computed from one value of the dilatancy on the loading curve. Using this approach, biaxial loading curves for confining pressures of 0 to 4 Kb were fit by varying only one constant which reflected the effect of confining pressure on the average crack volume.

Unloading is a very different process from loading in that it is a more linear process, with dilatancy persisting until unloading is complete. Detailed consideration of the local stresses at an open crack suggests that closure is by smooth linear backsliding when the stress falls below the failure stress. The unloading curves are described well by this process. To describe the process we find that three parameters must be obtained from experiment: $Y_D(\overline{P})$, f_V, and a factor related to the number of potential cracks/unit volume.

Implementation of the model in a computer code is straightforward. The finite element method is a natural choice. The effects of cracks can be incorporated in a simple and intuitively appealing way by treating the cracks as dislocations and using the equivalent body force description. This introduces a body force density that can be treated easily by finite elements. It also automatically includes crack interaction effects. Pore pressure effects are handled by using the interacting continua method to calculate the effective stresses. It is not clear how pore pressure will affect the strength of the cracks. Changing, oriented porosity implies that the permeability is anisotropic and variable. It is straightforward to include this effect in a fluid flow finite element code. The overall problem is highly nonlinear and must be solved iteratively.