RESEARCH ON NUMERICAL MODELING OF LIQUID GEOTHERMAL SYSTEMS

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We have developed a numerical code, called SCHAFF, which can treat problems involving slightly compressible fluid and heat transfer in multi-dimensional porous media. Solutions to the appropriate partial differential equations are obtained by the integrated finite difference method which is essentially equivalent to making mass and energy balances over finite sub-regions or elements. The resultant system of finite difference equations is solved by an iterative procedure and solutions to the fluid flow and energy equations are coupled by interlacing in time so that the temperature and velocity fields are interdependent. The useful concepts of fluid and thermal time constants as indicators of nodal response times and numerical stability limits are an inherent part of the numerical scheme.

In applying the numerical model to the problem of circulatory convection in saturated porous media, we have discussed the relevant aspects as they pertain to geothermal systems and show in Fig. 1 that results from SCHAFF on the relationship between the Rayleigh number and the dimensionless heat transfer coefficient or Nusselt number are in good agreement with numerical and experimental results from other authors. We then used the numerical model to extend these results to include the effects of temperature dependent parameters and density variations with pressure. Variations in fluid viscosity and thermal expansivity with temperature result in substantial differences in the values of the critical Rayleigh number for the onset of convection and the Rayleigh number-Nusselt number relationship compared with corresponding constant parameters results (Fig. 2). However, consideration of fluid density as a function of pressure produced no noticeable effect on convective motion.

Numerical simulations of more realistic models for circulatory convection show that for laterally bounded reservoirs, conduction of heat across the vertical sidewalls results in significant lowering of the rate of vertical heat transfer through the reservoir. For a laterally extensive reservoir, consideration of impermeable or less permeable layers above and below the convecting layer removes the restrictive assumption of constant temperatures boundaries on the permeable layer and has the effect of lowering the value of the critical Rayleigh number Ra_c while retarding convective heat transfer at values of Ra above Ra_c. The isotherm pattern for Ra = 100 is shown in **Fig. 3.**

Heat and mass transfer associated with hot spring systems was analyzed to determine the amount of heat lost by conduction to the rocks surrounding the spring conduit. As isolated cylindrical conduit model and a fault plane conduit model were considered, and the temperature drop in the hot spring water between the source reservoir and the surface due to the conductive heat loss as determined numerically as a function of flow rate is shown in Fig. 4. The steady state temperature distribution for the case where the rock surrounding the spring is impermeable (Fig. 5) shows that heat loss from the spring distorts the normally horizontal position of the isotherms out to distances comparable to the depth of the spring conduit. Conductive heat flux at the land surface is high near the spring but near the normal or background level beyond one conduit depth. Using a radiation boundary condition at the land surface as in Fig. 5 produces a more realistic surficial temperature distribution than a constant temperature boundary condition. The time required for the conductive thermal regime to equilibrate following the development of hot spring activity can be approximated by the expression $L^2\overline{\rho c}/2K_m$ where L is the depth to the source reservoir. For unconsolidated sediments with low thermal conductivity, the equilibration time is about 50,000 years for a reservoir at 1 km.

The effects of fluid circulation in the rock surrounding the spring conduit were examined for systems in which the equivalent Rayleigh number (in the absence of hot spring activity) was both above and below the critical value of $4\pi^2$. With $Ra<4\pi^2$, circulatory convection is set up due to the presence of the hot spring, but causes only slight effects on the thermal regime in the rock surrounding the spring conduit and on the conductive heat loss and temperature drop associated with the spring. For the case with $Ra>4\pi^2$, circulatory convection resulting from the temperature difference T_b-T_s between the source reservoir and the land surface dominates the thermal and hydrologic regimes and significantly reduces the conductive heat loss and temperature drop for the spring.

The results of this investigation demonstrate the usefulness of numerical modelling to describe the natural conditions of heat transfer and fluid flow in geothermal areas. Given preliminary thermal, hydrologic, and geochemical information, this technique can be used effectively as a guide to further data collection in undeveloped areas. As sufficient parametric and geometric information is obtained to allow simulation of the natural systems, the numerical model can be used to evaluate methods for energy development. In particular, studies are being planned of energy development under conditions of fluid reinjection which can maintain the reservoir fluid in a liquid state and possibly result in the recovery of significant fractions of stored heat. Numerical studies of the feasibility of storing and recovering waste thermal water from power plant operations in cold water aquifers are also anticipated. In addition, a modification of the SCHAFF program to include stress-strain behavior of porous media is currently being tested for simulation of land subsidence associated with geothermal reservoir development.

Further work on the calculational model is also planned. Incorporation of a suitable scheme for treating anisotropy and associated tensorial quantities such as permeability and thermal dispersivity would extend the range of the problems which could be analyzed with SGHAFF. It would also be desirable to include a general mesh-generating routine and a graphics capability for fluid velocity vector plotting.

References

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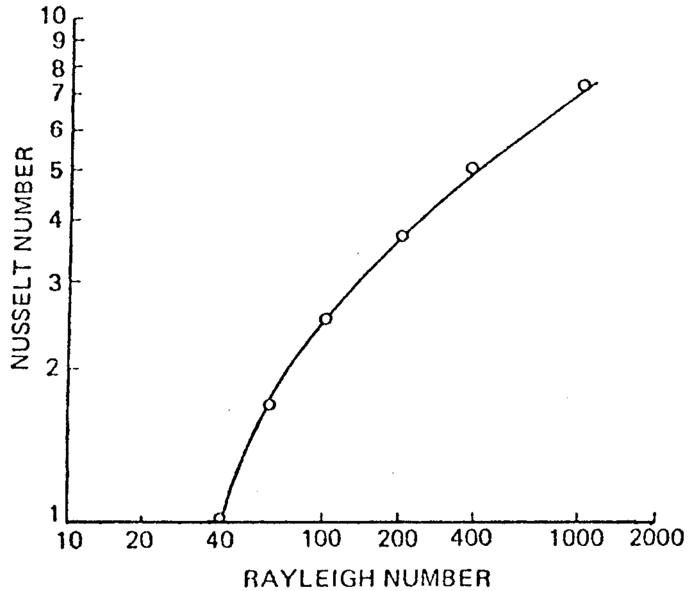

Figure 1 Rayleigh number versus Nusselt number for cellular convection in an extensive horizontal layer with constant fluid properties. Solid line based on SCHAFF result, open circles from numerical and experimental results by Combarnous and Bories (1973).

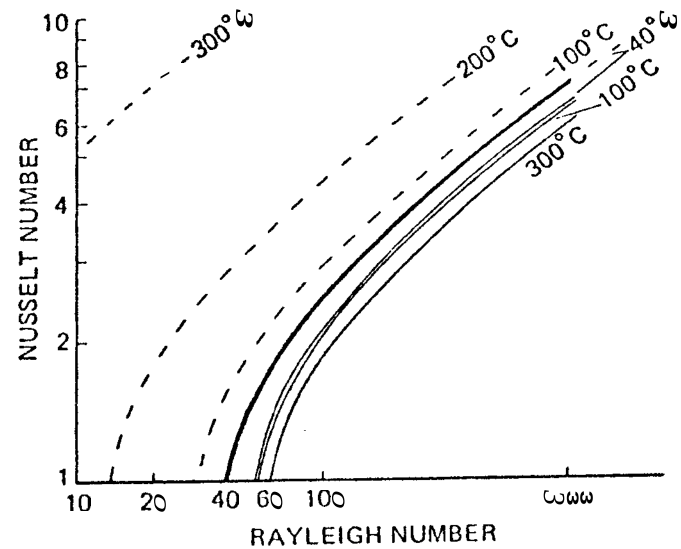

Figure 2. Results from SCHAFF for circulatory convection in an extensive horizontal layer with temperature-dependent fluid properties. Dashed curves for Ra evaluated at cold-side temperature T_o; solid curves for Ra evaluated at mean temperature $(T_1 + T_o/2)$. Heavy solid curve for constant fluid properties.

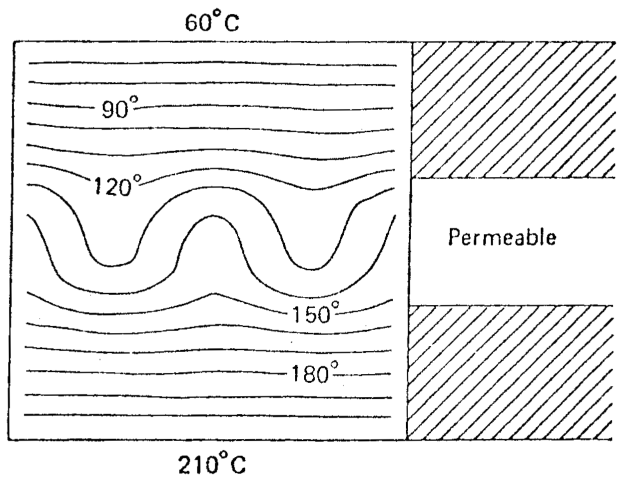

Figure 3. isotherms for 3-layer cellular convection model with Ra = 100.

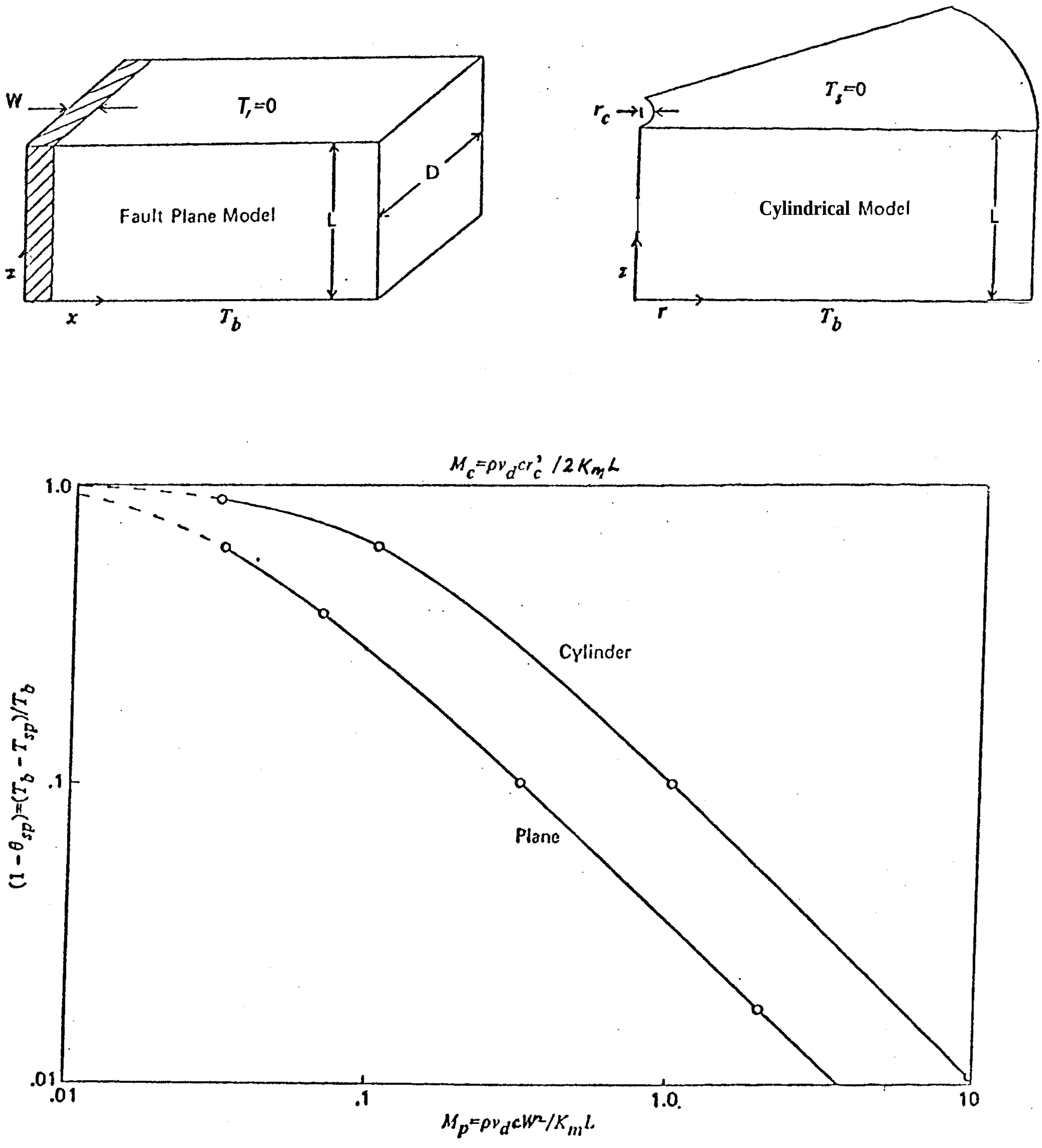

Figure 4. Relationships between dimensionless flow rates (M_c, M_p) and dimensionless temperature drop ($1-\theta_{sp}$) due to conductive heat loss in cylindrical and fault plane hot spring models.

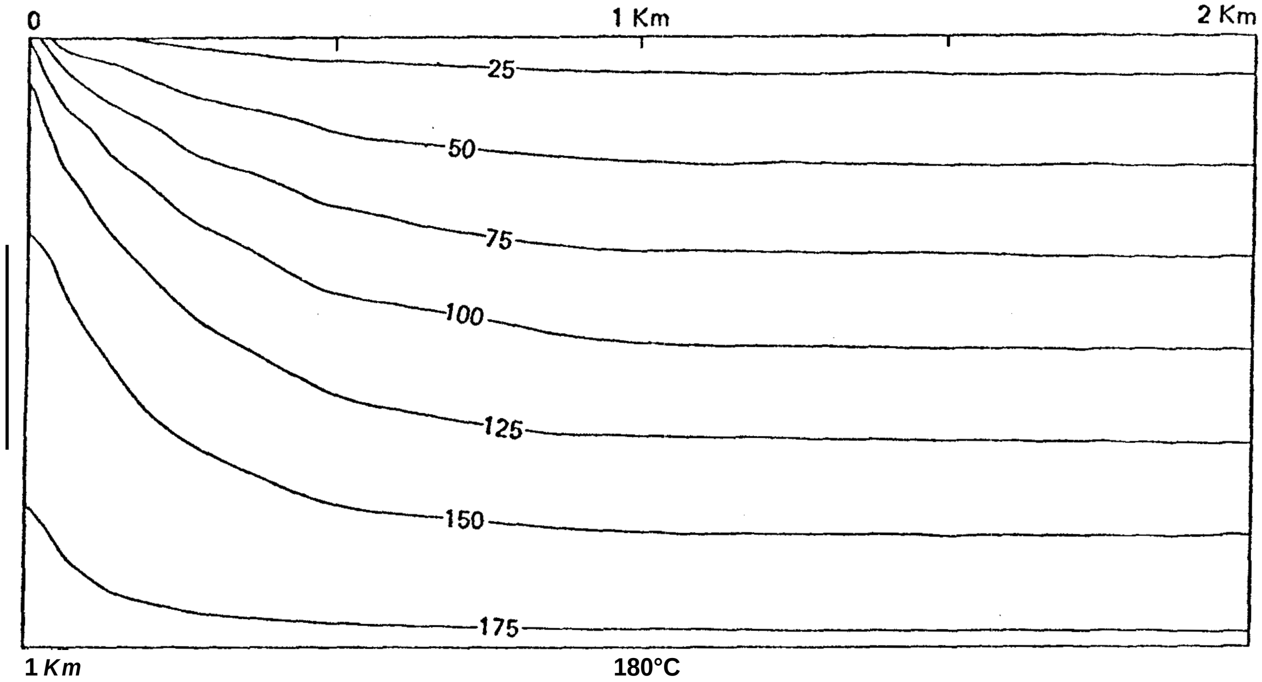

Figure 5. Steady state temperature distribution in fault plane hot spring model with discharge = 10^5 Kg/d, W = 10m, D = 1 Km, and Ra = 0 (k = 0), and H = 10^{-6} cal/sec -°C -cm^2 at land surface.