CONF-8704110--13

SAND--87-0923C

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RECENT PROGRESS IN MAGMA ENERGY EXTRACTION

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ABSTRACT

Ongoing research in the area of Magma Energy Extraction is directed at developing a fundamental understanding of the establishment and long term operation of an open, direct-contact heat exchanger in a crustal magma body. The energy extraction rate has a direct influence on the economic viability of the concept. An open heat exchanger, in which fluid is circulated through the interconnecting fissures and fractures in the solidified region around drilling tubing, offers the promise of very high rates of heat transfer. This paper discusses recent research in five areas: (1) fundamental mechanisms of solidifying and thermally fracturing magma, (2) convective heat transfer in the internally fractured solidified magma, (3) convective flow in the molten magma and heat transfer from the magma to the cooled heat exchanger protruding into it, (4) numerical simulation of the overall energy extraction process, and (5) the thermodynamics of energy conversion in a magma power plant at the surface. The studies show that an open heat exchanger can be formed by solidifying magma around a cooled borehole and that the resulting mass will be extensively fractured by thermally-induced stresses. Numerical models indicate that high quality thermal energy can be delivered at the wellhead at nominal rates from 25 to 30 MW electric. It is shown that optimum well circulation rates can be found that depend on the heat transfer characteristics of the magma heat exchanger and the thermodynamic power conversion efficiencies of the surface plant.

INTRODUCTION

Magma is a huge potential resource. The work of Smith and Shaw (1978) resulted in an estimate for the U. S. of 50,000 to 500,000 quads contained in magma at temperatures above 600°C and at depths shallower than 10 km. Before industry can evaluate the future economic viability of magma energy, several key areas require further study and technology development.

The Magma Energy Extraction Project, initiated by the Geothermal Technology Division of DOE during FY 84, is assessing the engineering feasibility of extracting high quality thermal energy directly from crustal magma bodies. This program follows a seven year study that demonstrated the scientific feasibility of the magma energy concept [Colp (1982)]. At the conclusion of the study, many of the energy extraction concepts were demonstrated by drilling into the molten zone of Kilauea Iki lava lake, emplacing energy extraction hardware, and operating the system for a period of five days [Hardee et al. (1981)]. The present project is organized to address: (1) resource location and definition, (2) drilling, (3) magma characterization and materials compatibility, and (4) energy extraction. We have an ultimate objective of drilling into an active crustal magma body and conducting an energy extraction experiment. The location for this experiment has been selected in Long Valley Caldera, California, where magma drilling targets have been identified.

The rate at which electricity can be generated from a magma well is a major factor in determining its economic viability. However, determination of such rates is complex because of the uncertainties in the nature and properties of in situ magma bodies, and the complexity of potential heat exchange processes within the magma. Our approach has been to perform fundamental engineering analyses in conjunction with phenomenological experiments in order to develop conceptual models of the magma heat exchanger and obtain estimates of potential rates of energy extraction. In this paper, we briefly summarize recent research in the area of energy extraction.

PRIOR ANALYSES

Magma is a multicomponent material that usually exists in the crust at temperatures near or below its liquidus. At these temperatures, the material is a mixture of liquid and crystalline phases and behaves like a high Prandtl number, non-Newtonian fluid. Much of the early work, [Hardee (1981), Hardee, et al (1981), Dunn, et al (1983)], was directed at evaluating natural convection heat transfer rates in magma, both analytically and experimentally. Heat flux measurements were made in degassed basaltic lava at temperatures near and below the liquidus and were in excellent agreement with calculations based on a boundary-layer analysis for a high Prandtl number, non-Newtonian fluid. [Hardee and Dunn (1981)]. Experiments were also performed at in situ conditions of temperature, pressure, and volatile content, [Dunn et al. (1983)], and confirmed predictions that significantly higher heat transfer rates are obtained at in situ conditions where volatiles have an important effect on viscosity.

This work was supported by the U. S. Department of Energy at Sandia National Laboratories under Contract DE-AC04-76DP00789.

Parts of this paper were previously published in the Proceedings of the Twelfth Workshop on Geothermal Reservoir Engineering, Stanford University, January 1987.

DISCLAIMER

Hardee (1981) used boundary-layer analysis to predict thermal energy extraction rates for several magma compositions assuming a "closed" heat exchanger system where fluid is contained within a pipe and does not directly contact magma. Hardee's calculations show very high heat transfer rates (resulting in 20 to 80 MWth/well) for basaltic magma which has relatively low viscosity. Rhyolitic magma, with much higher viscosity, was predicted to offer lower energy extraction rates, on the order of 4 to 19 MWth per well.

An alternative "open heat exchanger" concept for magma energy extraction uses direct fluid/magma contact. Analyses by Dunn (1983) showed that thermal stresses created in magma solidifying around a cooled borehole would be sufficient to cause fracturing. By circulating a heat transfer fluid through the solidified and fractured magma, greatly increased surface area and energy extraction rates could be achieved. The concept was tested in the 1981 Kilauea Iki experiments. During a five day period, energy extraction rates were found to increase with time (indicating growth of the fractured region) reaching a value more than 10 times the expected value for a closed heat exchanger in the same borehole [Dunn (1983)].

The present magma energy program is focused on silicic magma systems which are most representative of magma bodies expected at most western U. S. sites. An economic analysis of magma power generation [Carson and Haraden (1985)] indicates that closed heat exchangers can have only limited application in silicic magmas. However, open, direct contact heat exchanger systems operating at depths up to 6 km are shown to be roughly competitive with existing sources of energy for power generation. As a result, our recent work in energy extraction is concentrated on extraction processes using fluid circulation through solidified/fractured magma.

THE OPEN HEAT EXCHANGER

Figure 1 shows our current conceptual representation of a single well during steady operation in an open heat exchanger mode. The well is cased above the magma chamber and the injection tube is surrounded by a fractured, solidified region whose radial extent is determined by the rate of energy extraction. There is an intermediate transition zone which behaves as a plastic solid and does not support fracturing. Because of heat transfer to the exchanger, large scale natural convection is induced within the chamber with magma flowing down the outer solidification boundary.

The formation and operation of an open heat exchanger, as presently envisioned, involves numerous complex processes. Our current research follows two paths: first, research into the formation of a fractured, solidified region suitable for heat exchange, and second, analysis of the local heat exchange processes within the fractured mass and in the external convecting magma. The remainder of this paper summarizes recent activities in these two areas.

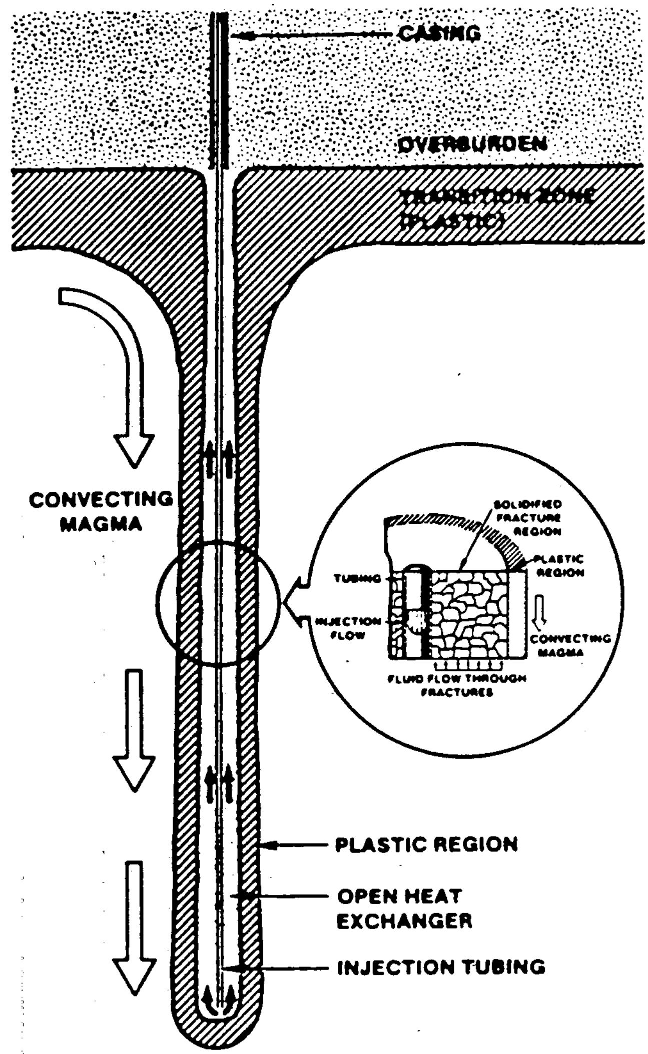

Figure 1. Conceptual representation of open heat exchanger with fluid flow through fractured, solidified magma.

Thermal Fracturing of Solidifying Magma

Dunn (1983) and Wemple and Longcope (1986) developed theoretical models to describe thermal stress fracturing in a solidified magma region surrounding a borehole. The models only consider stresses caused by temperature gradients in a solid annulus. Secondary fracturing due to flow in the initial fractures or pressure driven hydraulic-type fracturing are not included. The analyses predict vertical and horizontal fractures even for large over-burden pressure. Wemple and Longcope (1986) show that horizontal fractures should predominate and give estimates for their spacing and aperture. For a basaltic lava and wellbore parameters typical of those for the Kilauea Iki experiment, a fracture spacing of 1 cm with aperture of 0.1 mm is obtained. The analysis also predicts that the fractures will extend almost to the outer limit of the solidified region.

An experimental program was recently begun to examine the qualitative features of the initiation and propagation of thermal stress fractures in solidifying magma simulant materials. Initial thermal stress fracturing experiments were performed in thick-walled Sandia "S" glass cylinders (6.35 cm OD x 10.16 cm L) which were cast, annealed, and axially cored. The cylinders were fitted with a 304 SS tube to allow injection of air or water into the center bore after preheating the cylinders to initial temperatures ranging from 200 to 400°C. Figure 2 illustrates a typical fractured thick-walled cylinder which was preheated to 200°C then cooled at the inner bore with water at 20°C. Extensive fracturing of the specimen occurs within seconds after cooling is initiated. The fracture distribution is in general agreement with theoretical predictions. In accordance with the theory, both horizontal and vertical fractures were produced and no cylindrical fractures occurred. At both 200 and 400°C, there were substantially more horizontal than vertical fractures.

Several laboratory experiments have been performed to qualitatively evaluate the processes by which a simulant glass solidifies and fractures from an initially molten state under the influence of a cooled inner boundary. The phase change from a molten to solid state will occur at a rate which is governed by the rate at which heat is removed from the inner boundary. Solidification will be slow compared to the speed at which fractures propagate through the solid, hence, fractures will initiate and propagate rapidly into the solid phase until thermal stresses are relieved. In the melt solidification experiments, an axial cooling flow tube was pre-cast in an "S" glass cylinder which was then re-melted in an induction furnace at approximately 750°C. Water at room temperature was allowed to flow through the center tube to chill the melt at a controlled rate. Figure 3 shows a cross-section of a sample that was chilled rapidly. The rapid cooling of the tube resulted in a glassy phase nearest the tube surrounded by a region of mixed glass and crystalline phases. The inner glass phase is extensively fractured but its radial extent is limited. The outer region has fewer fractures, but extensive interconnection between fractures was observed. In this experiment the outer melt zone was maintained at 1000°C and the cooling tube wall was estimated to be no greater than 150°C.

Secondary fracturing processes, not yet evaluated, may play a significant role in the formation of the fractured region. Fluid in direct contact with the cooled inner surface will flow into the primary fractures as long as new fractures are propagated. Fluid flow will have two effects on the rate and extent of fracturing. First, heat transfer from the primary fracture walls to the flow will introduce temperature gradients that tend to produce secondary fractures normal to the principal fractures. Second, fluid pressure in the primary fracture may exceed the confining pressure on the solidified region such that the fluid will exert a net hydraulic pressure on the fracture walls and enhance the propagation. Our present approach is to first clarify understanding of the fracture mechanics in a homogeneous medium using simulant materials, then introduce secondary effects one at a time and assess their importance. One of the most important facets of this experimental program is improving our understanding of scaling laws in the mechanics of thermal fracturing that will allow extrapolation of laboratory observations to the full-scale heat exchanger.

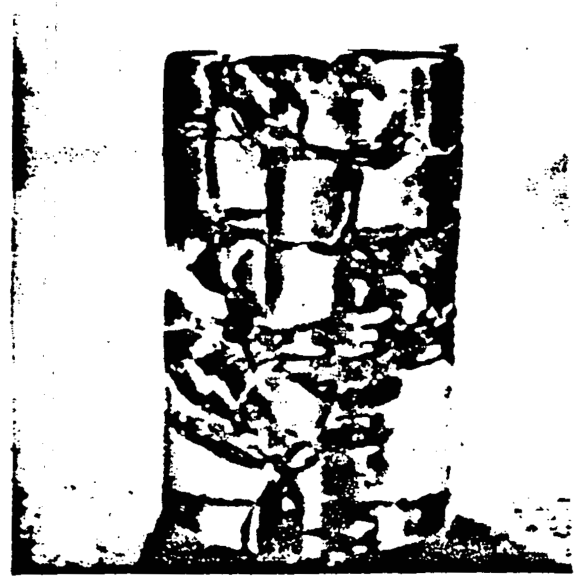

Figure 2. Thick walled glass cylinder thermally fractured at 200°C.

Figure 3. Cross-section of pre-melted glass cylinder after solidification induced by cooling flow through center tube.

Heat Transfer in the Open Heat Exchanger

As a first approximation to heat transfer within the open direct contact heat exchanger, the solidified and fractured region surrounding the borehole is modeled as a porous medium with local thermal equilibrium between the solid and fluid phases. The porous medium can be completely characterized by specification of its effective permeability, K, and the effective saturated thermal conductivity, k. Order of magnitude estimates for the permeability were obtained using the cubic fracture model of Snow (1968) with the fracture geometry predictions of Wemple and Longcope (1986). Due to the small volume of interstitial fluid, the effective thermal conductivity was taken as that for solidified magma. Hardee (1981) presents data showing typical values on the order of 3 W/m-K for rhyolitic magmas.

Flow and heat transfer within the porous annular region is, at this level of approximation, described by the standard Darcy formulation for porous media [Dunn et al (1987)]. For an annulus in which the outer wall temperature is held constant at T_o and the inner wall temperature at T_i, the fully-developed temperature profile is the same as the conduction profile, and the mixed mean Nusselt numbers are given by:

$$Nu_i = \frac{2(1-r^*)}{r^* \ln r^* \; \frac{1}{1-r^{*2}} + \frac{1}{2 \ln r^*}}$$

$$Nu_o = \frac{2(1-r^*)}{\ln r^* \; 1 - \frac{1}{1-r^{*2}} - \frac{1}{2}}$$

where $r^* = r_i/r_o$. Similar expressions may be found for the case of uniform heat flux walls by using linear superposition of partial solutions for heating on one wall. These expressions are used to form the lower limit of the open heat exchanger heat transfer coefficient.

Various effects can alter the heat transfer within the porous annulus and significantly affect the net energy extraction. Among the most important considerations are developing flow effects and local buoyancy. The developing thermal field for fully-developed slug flow in an annular region, may be found by direct analogy to the problem of transient cooling of an annular-shaped billet. For the case of an insulated inner boundary and a constant temperature outer boundary, the solution for the temperature field is shown by Carslaw and Jaeger (1959). Two results from this analysis are of interest. First, the mixed mean Nusselt number in the entry region is much higher than its asymptotic value. Second, preliminary calculations indicate that fully-developed thermal conditions may not be attained for the range of Peclet number and annulus aspect ratios of current interest. The net result is that the overall heat transfer coefficient for the annulus may be from two to five times higher than the conservative fully-developed estimate.

Local buoyancy effects can become important in determining the overall heat transfer if temperature gradients within the annulus are severe. The relative importance of the two mechanisms can be found by inspection of the ratio of the local forced flow Peclet number, Pe, and the local Rayleigh number, Ra, which is indicative of the local buoyancy. Using geometry and property data expected for operation of an open direct contact heat exchanger in magma, the above dimensionless groups lie within the range: $0.18 < Ra/Pe < 4.0$. At the low end, buoyancy effects are negligible, but for Ra/Pe on the order of 1.0, local buoyancy effects may substantially affect the heat transfer. To evaluate this effect, we are currently performing full numerical solution of using the finite element code MARIAH [Gartling and Hickox (1982)] in a cylindrical annulus with both constant temperature and constant heat flux boundary conditions. An example of this effect can be seen in Figures 4 and 5 which give calculated results for an experimental facility at the University of Utah. Figures 4(a) and 4(b) show streamlines in the annular region with the outer boundary at constant temperature, and an insulated inner boundary. Figure 4(a) is for pure forced convection and the flow is very nearly a uniform slug flow. For non-negligible local buoyancy effects, Fig. 4(b), flow is entrained towards the heated boundary in the lower part of the annulus resulting in increased mass flow within the thermal boundary layer. The upward velocity through the annulus at the horizontal midplane is shown in Fig. 5. The net result of this buoyancy-assistance is that convection near the heated boundary may be enhanced above that for forced slug flow. The degree of enhancement depends on the boundary conditions, the ratio of Ra/Pe, and the annulus geometry.

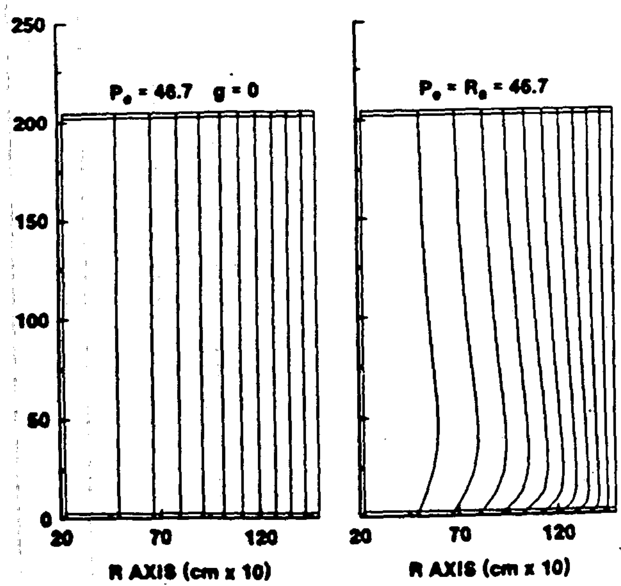

Figure 4. Streamlines--U. of Utah experiment simulation: (a) Forced slug flow, (b) buoyancy-assisted flow.

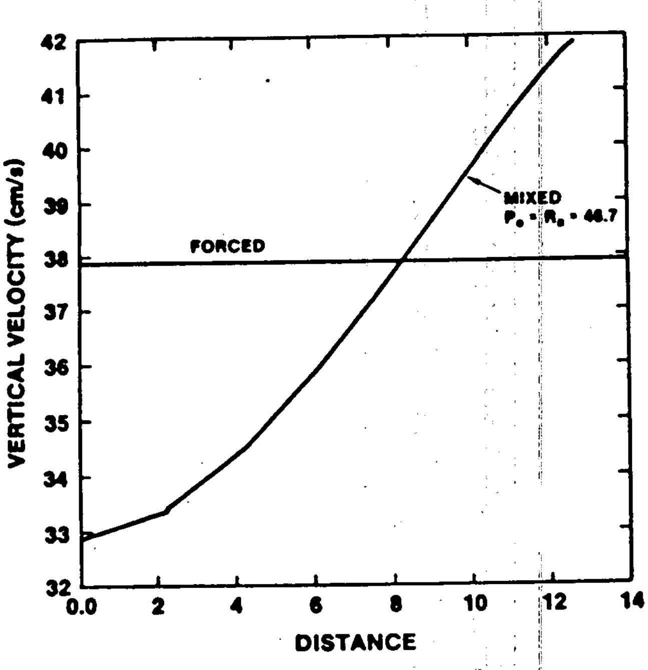

Figure 5. Vertical velocity profiles at horizontal midplane--U. of Utah experiment simulation.

To confirm the numerical studies of the porous open heat exchanger experiments in buoyancy-assisted porous media flows are being conducted at the University of Utah [Boehm et al (1987)]. The experimental apparatus uses an annular space formed between two concentric pipes having diameters of 1.25 and 11.5 inches. The space is filled with 1mm ceramic microspheres to form a porous bed. Water can be injected at the base either in a uniform slug flow from a supply header, or as a source flow at the base of the center tube. The outer walls are maintained at uniform temperature. Figure 6 shows a cross-section of the main apparatus with the porous fill material in place. The temperature distribution in the bed is measured at seven axial locations. Typical measured temperatures are shown in Figures 7 and 8. The most striking observation that may be made thus far is that for the range of scaled flow rates in question, the temperature profiles are not at all fully-developed. The thermal boundary layer does not penetrate to the inner wall under any conditions representative of the magma open heat exchanger. The immediate ramification is that local heat transfer coefficients will be significantly higher than the fully-developed values used in the numerical simulation discussed in the following section. Experiments are currently underway which will cover a wide range of conditions in both forced and buoyancy-affected flows.

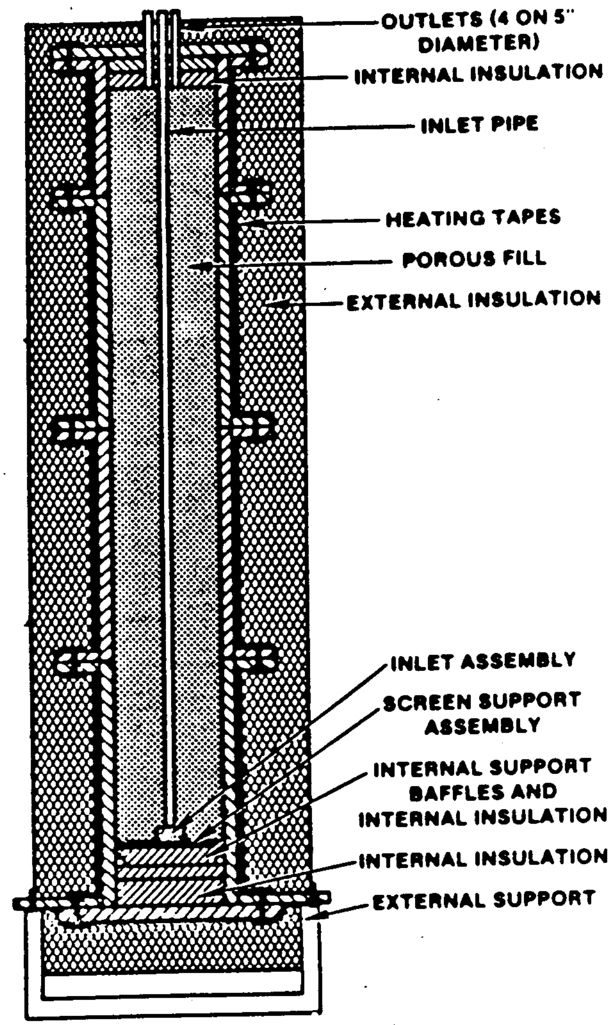

Figure 6. Cross-section of Open Heat Exchanger Experimental Apparatus.

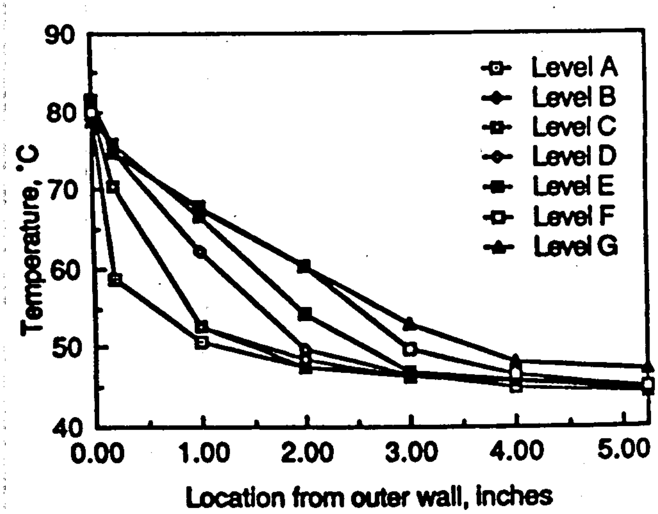

Figure 7. Radial temperature profiles at six axial locations--Pe=1429.3, Ra=468.9.

CONVECTIVE FLOW AND HEAT TRANSFER IN THE MAGMA CHAMBER

As shown in Figure 1, the conceptual open heat exchanger is surrounded by convecting molten magma. The magnitude of the convective heat flux available at the outer surface of the heat exchanger essentially depends on two phenomena:

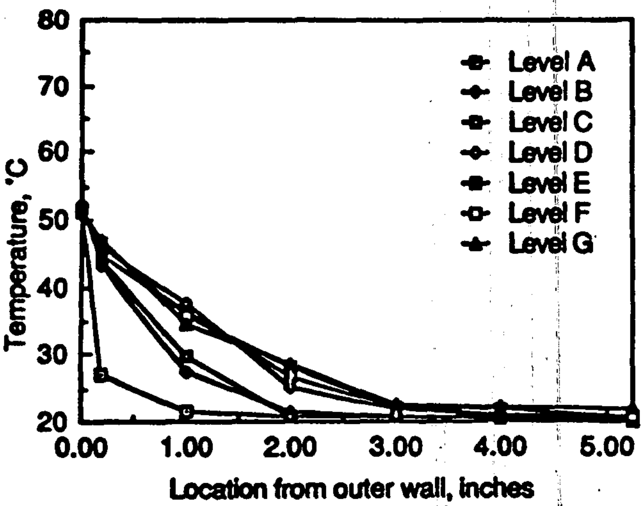

Figure 8. Radial temperature profiles at six axial locations--Pe=3338.3, Ra=88.53.

one, the vigor with which fresh, hot magma is transported to the plastic region by chamber convection, and two, the efficacy of convection and diffusion in the boundary layer next to the heat exchanger. A typical chamber may have representative length scales on the order of 5 km with magma temperatures ranging from 650° to 900°C. The representative chamber Rayleigh number may be on the order of 10^{16} which is far greater than the critical Rayleigh number below which one could expect steady, laminar convection. The physics of turbulent natural convection in such enclosures are not well understood. The problem is further complicated by large variations in the magma viscosity. The physics of the boundary layer interaction at the cooled heat exchanger walls are equally complex and poorly understood.

In order to better understand the fundamental mechanisms of the chamber and boundary layer convection, and ultimately, to improve our engineering estimates of the heat flux available at the exchanger, we have begun a laboratory study in which we simulate the most important mechanisms in a scaled experiment. The apparatus consists of a clear, plexiglas enclosure with a typical dimension of 50 cm. The simulant working fluid is corn syrup. Figure 9 shows a schematic of typical boundary conditions which may be simulated with the apparatus. At the present time, the enclosure is configured with two-dimensional strip heating at the bottom surface and cooling at the top surface with insulated side surfaces, as in the lower left figure. These boundary conditions are representative of a chamber which is fed from a single source. Among the diagnostic measurements to be made are full-field mapping of velocity and temperature fields using laser Doppler velocimetry, traversing temperature probes, encapsulated liquid crystal thermography, and time lapse photography of the convecting fluid seeded with tracer particles. The first series of experiments are currently underway. It is anticipated that the experiments will provide data for comparison with numerical simulation.

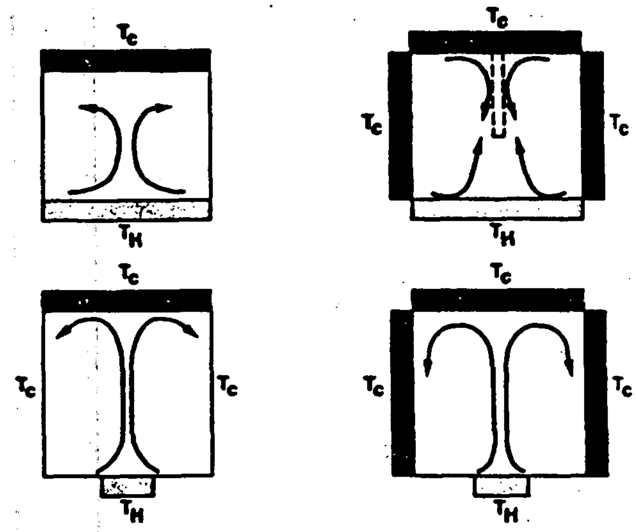

Figure 9. Magma Chamber Convection Simulation Experiments: possible boundary conditions.

NUMERICAL SIMULATION OF SINGLE WELL ENERGY EXTRACTION

Hickox and Dunn (1985) used simplified models to obtain first order estimates of the complete energy extraction process including heat transfer in counterflowing fluids from the surface to the magma zone, with possible heat loss to the overlying formation. They made several important observations. Reasonable hole diameters, on the order of 0.194 m in the magma zone were shown to be sufficient for large energy extraction rates. Using concentric pipes with fluid flow down the annulus and return through an insulated core, the fluid receives a net heat gain from (not a loss to) the formation above a magma body. A relatively modest insulation thickness, on the order of 1.5 cm, was found to provide good isolation between the hot return fluid and cold injection fluid. Finally, it was observed that for a given magma heat transfer coefficient, an optimum flow rate exists that maximizes electric power production. For the open heat exchanger, which was assumed to have an overall heat transfer coefficient ten times that for the closed exchanger, optimum flow rates lead to predicted energy extraction rates of about 25 MW electric.

A numerical code called MAGMAXT has recently been developed to simulate the flow of compressible, homogeneous water/vapor within the well and heat exchanger with heat transfer to and from the convecting magma and the overlying formation. The code allows arbitrary specification of a contiguous flow path through regions such as tubing, concentric pipe annulus, or heat exchanger. Heat transfer to or from the fluid stream is allowed through the specification of overall heat transfer coefficients between the counterflowing flow streams and between the fluid and formation or magma. Heat transfer is assumed to occur in the radial direction only. Convective heat transfer coefficients within the tube or annulus are evaluated assuming fully-developed turbulent flow using commonly available correlations for single or two-phase flow. Separate correlations are used in the sub-cooled, saturated, super-heated and super-critical regions. The overlying formation is assumed to be homogeneous, with constant properties, and conduction to the formation is modeled using the quasi-steady assumption of Ramey (1962).

MAGMAXT has been used to simulate the flow and energy extraction rate in the base case geometry which was previously investigated by Hickox and Dunn (1985). The well depth is 5 km followed by a 1 km heat exchanger in magma. The open heat exchanger is assumed to be a porous annulus whose outer diameter can vary depending on the heat exchange rate. Results shown in Figures 10 through 14 are found using fully-developed slug flow Nusselt numbers which are the most conservative, i.e. lowest, values which can be attained. The present results provide a realistic lower limit on expected energy extraction rates and point out various important characteristics in the single well energy extraction process.

By specification of the injection pressure and mass flow rate, the flow state throughout the circulation path can be computed in an iterative marching procedure by MAGMAXT. Specification of a wellhead back-pressure is optional. For a specified mass flow rate, the injection pressure specified is acceptable if the exit pressure is equal to the specified wellhead pressure or is greater than ambient if a wellhead pressure is not specified.

Figure 10 shows the temperature of the circulating water at a flow rate of 50 kg/s (800 gal/min). The flow path is specified as down the wellbore annulus (A-B), down the insulated tubing in the heat exchange region (B-C), up the porous annulus (C-D), and up the insulated wellbore tubing (D-E). At this relatively high flow rate, there is little temperature change in the wellbore in both the injection and return directions. Within the heat exchanger, the temperature increases from 100 to 300°C.

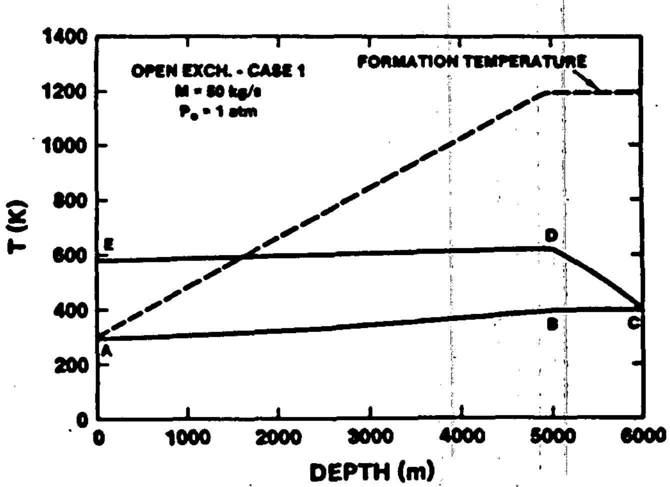

Figure 10. Flow temperature for M=50 kg/s; open heat exchanger base case.

The temperature of the plastic zone around the heat exchanger is maintained at a constant 900°C, and the available heat flux is specified as 1 kW/m^2.

As seen in Fig. 11, the pressure increase in the injection path is due almost entirely to the hydrostatic pressure of the fluid in the sub-cooled state. As the fluid is heated in the heat exchange region, its density decreases, hence, the pressure in the return path decreases less rapidly than in the injection path. Because of the net density imbalance between the two flow paths, the flow loop has the capacity for natural thermosyphoning. In the current example, the inlet pressure was specified as ambient, hence the well is self-flowing at a flow rate of 50 kg/s with a wellhead pressure of roughly 15 MPa.

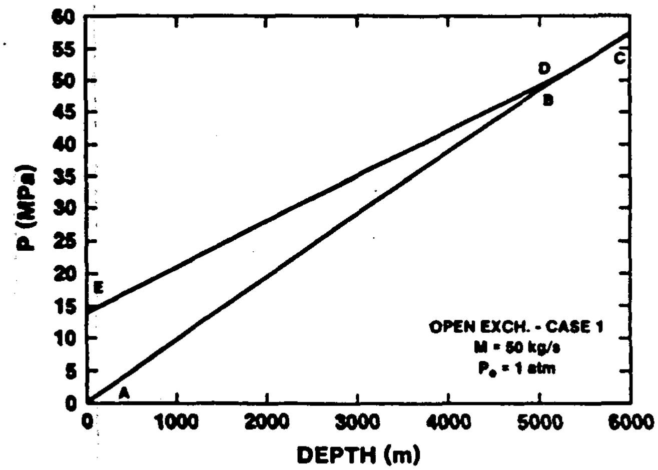

Figure 11. Flow pressure for M=50 kg/s; open heat exchanger base case.

The P-h diagram for the flow, Fig. 12, illustrates the fluid phase in the loop. The hydrostatic pressure increase in the injection path results in pressures well above the critical pressure at the inlet to the heat exchanger. Because of the large flow area in the open heat exhanger annulus, the fluid is heated with very little pressure drop but with an accompanying density decrease. Depending on the flow rate and the specified wellhead back pressure, the exiting fluid state may be superheated vapor, supercritical, or highly-pressurized hot water, as in the current example. No realistic operating conditions have been found in which the return state is saturated vapor, hence, two-phase choking in the return tubing does not limit the available flow rate as is commonly the case in vapor producing geothermal wells.

The solidification diameter of the open heat exchanger depends directly on the rate of cooling since the energy convected by the fluid must equal the energy convected by the magma to the outer boundary of the heat exchanger. Figure 13 shows the resulting diameter of the exchanger as a function of depth for flow rates of 10, 70, and 100 kg/s. For low flow rates, the diameter changes rapidly since the fluid

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