PROCEEDINGS, Twelfth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 20-22, 1987
SGP-TR-109

MAGMA ENERGY EXTRACTION

J. C. Dunn, A. Ortega, C. E. Hickox, T. Y. Chu, R. P. Wemple
Sandia National Laboratories
Albuquerque, NM 87185

R. F. Boehm
University of Utah
Salt Lake City, UT 84112

ABSTRACT

The rate at which energy can be extracted from crustal magma bodies has an important influence on the economic viability of the magma energy concept. Open heat exchanger systems where fluid is circulated through solidified magma offer the promise of high energy extraction rates. This concept was successfully demonstrated during experiments in the molten zone of Kilauea Iki lava lake. Ongoing research is directed at developing a fundamental understanding of the establishment and long term operation of open systems in a crustal magma body. These studies show that magma solidifying around a cooled borehole will be extensively fractured and form a permeable medium through which fluid can be circulated. Numerical modeling of the complete magma energy extraction process predicts that high quality thermal energy can be delivered to the wellhead at rates that will produce from 25 to 30 MW electric.

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 previous project, 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 magma 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.

A magma energy technology of interest to this conference is energy extraction due to its similarities with reservoir engineering in that both must treat fluid flow and heat transfer in fractured media. 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 past and recent research in the area of energy extraction.

PRIOR ANALYSES

Magma is a multicomponent material that usually resides 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 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

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

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.

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 high-level magma bodies in the crust and the type 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.

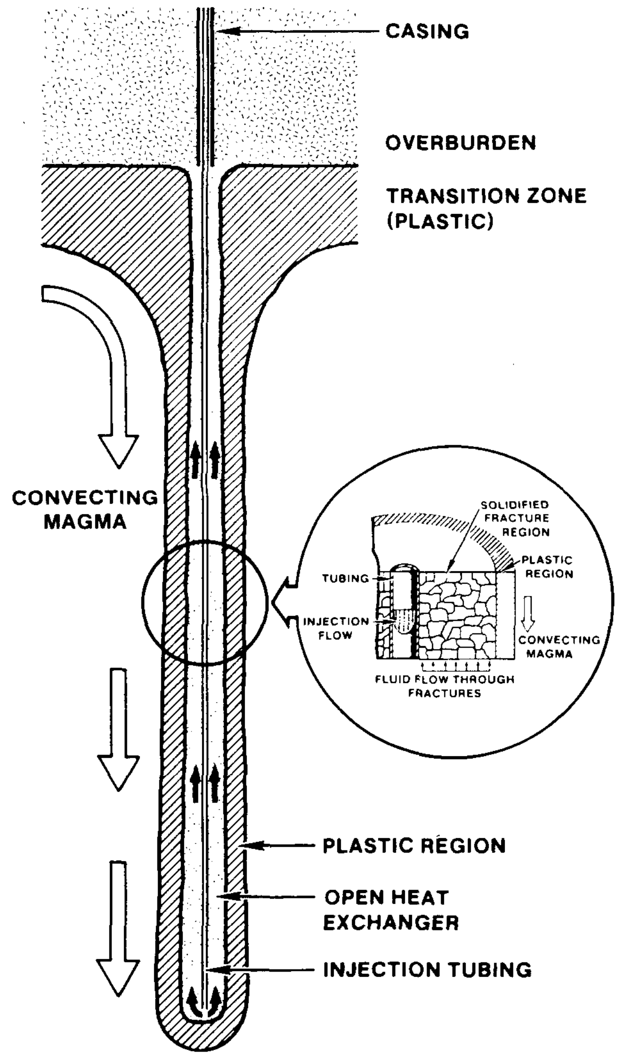

Figure 1. Conceptual representation of open heat exchanger with fluid flow through fractured, solidified magma.

The formation and operation of an open heat exchanger, as presently envisioned, involves numerous complex processes. Our current research approach follows two paths: one, research into the formation of a fractured, solidified region suitable for heat exchange, and two, 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.

Thermal Fracturing of Solidfying 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 predicts vertical and horizontal fractures even for large overburden 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 and semi-quantitative 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 calculated to be no greater than 150°C.

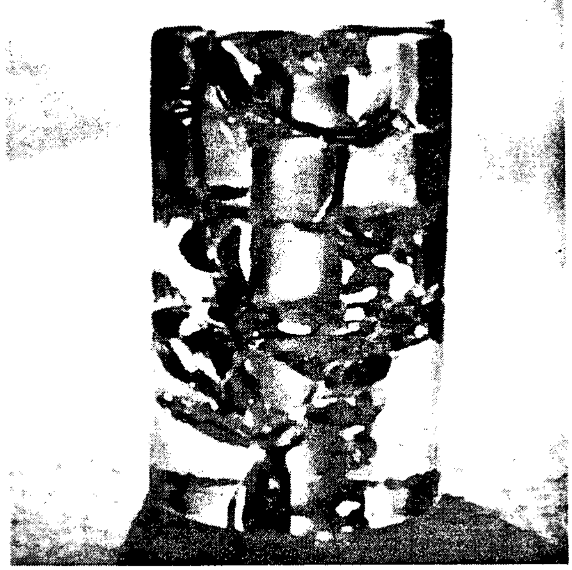

Figure 2. Thick walled glass cylinder thermally fractured at 200°C.

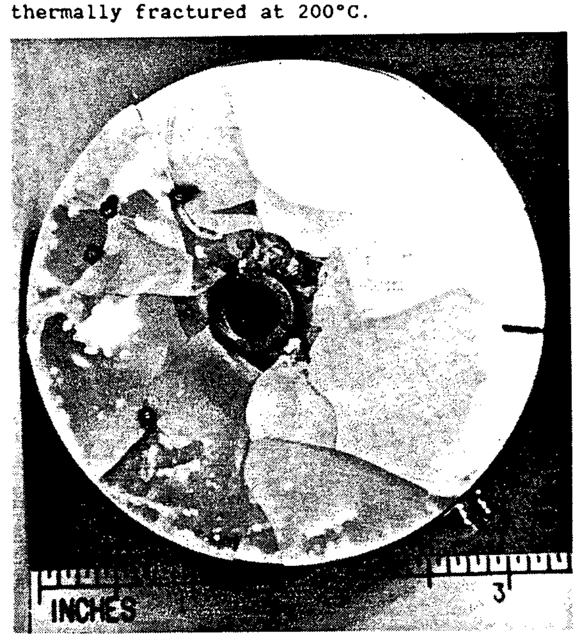

Figure 3. Cross-section of pre-melted glass cylinder after solidification induced by cooling flow through center tube.

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.

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. The conservation equations in differential form are given as:

$$\text{mass:} \quad \frac{1}{r}\frac{\partial}{\partial r}(r v_r) = \frac{\partial}{\partial z}(v_z) = 0 \qquad (1)$$

$$\text{momentum:} \quad v_r = -\frac{K}{\mu}\frac{\partial}{\partial r}(p + \rho g z) \qquad (2)$$

$$v_z = -\frac{K}{\mu}\frac{\partial}{\partial z}(p + \rho g z) \qquad (3)$$

$$\text{energy:} \quad v_z \frac{\partial T}{\partial z} + v_r \frac{\partial T}{\partial r} = \alpha \nabla^2 T \qquad (4)$$

where r and z are the radial and axial directions, respectively, K is the permeability, μ is the fluid viscosity, α is the effective thermal diffusivity and ρ is the fluid density. For an annular porous region the lower limit on the local mixed mean Nusselt number is found under the conditions of fully-developed slug flow, and fully-developed temperature profiles. 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 number is given by:

$$Nu_i = \frac{2(1-r^*)}{r^* \ln r^* \left(\frac{1}{1-r^{*2}} + \frac{1}{2\ln r^*}\right)} \qquad (5)$$

$$Nu_o = \frac{2(1-r^*)}{\ln r^* \left(1 - \frac{1}{1-r^{*2}}\right) - \frac{1}{2}} \qquad (6)$$

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 are omitted here for brevity.

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 equations [1-4] 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

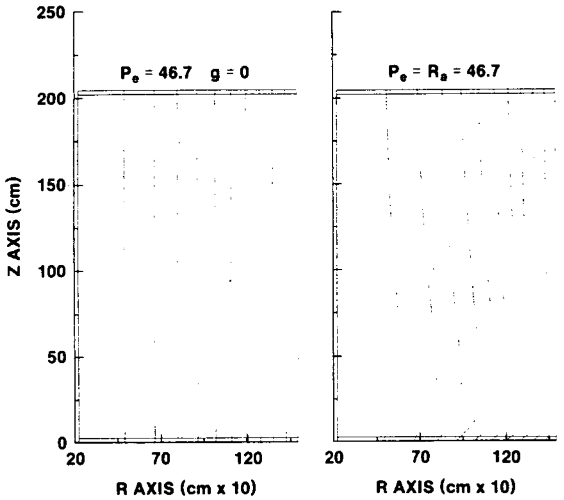

Figure 4. Streamlines--U. of Utah experiment simulation: (a) Forced slug flow, (b) buoyancy-assisted flow.

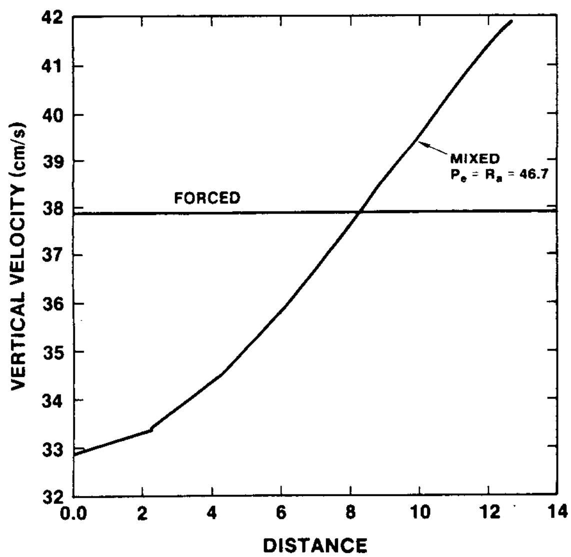

Figure 5. Vertical velocity profiles at horizontal midplane--U. of Utah experiment simulation.

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.

To complement the numerical studies of the porous open heat exchanger R. F. Boehm is conducting experiments in buoyancy-assisted porous media flows at the University of Utah. 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 microshperes 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. The temperature distribution in the bed is measured at seven axial locations. Experiments are currently underway which will cover a wide range of conditions in both forced and buoyancy-affected flows.

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 supercritical 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 6 through 10 are found using the fully-developed slug flow Nusselt numbers given by Eqns. [5] and [6]. The fully-developed values of the Nusselt number are the most conservative, i.e. lowest, values which can be attained. As discussed in the previous section, the heat transfer can be considerably higher than this value due to the effects of developing flow and buoyancy. 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 6 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. 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.

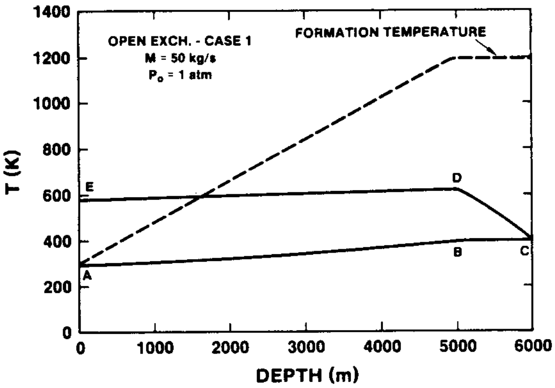

Figure 6. Flow temperature for M=50 kg/s; open heat exchanger base case.

As seen in Fig. 7, the pressure increase in the injection path is due almost entirely to the hydrostatic pressure of the fluid in the subcooled 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 back-pressure of roughly 15 MPa.

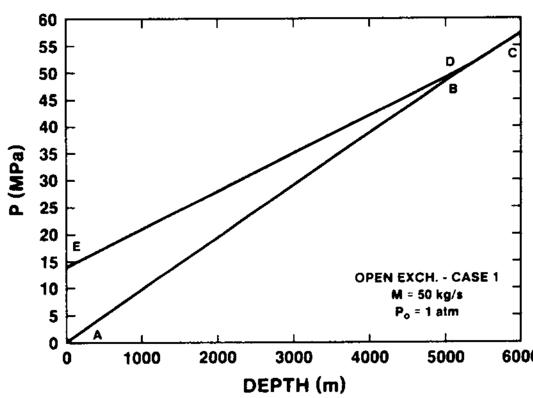

Figure 7. Flow pressure for M=50 kg/s; open heat exchanger base case.

The P-h diagram for the flow, Fig. 8, illustrates the fluid phase in the loop. The hydro- static 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.

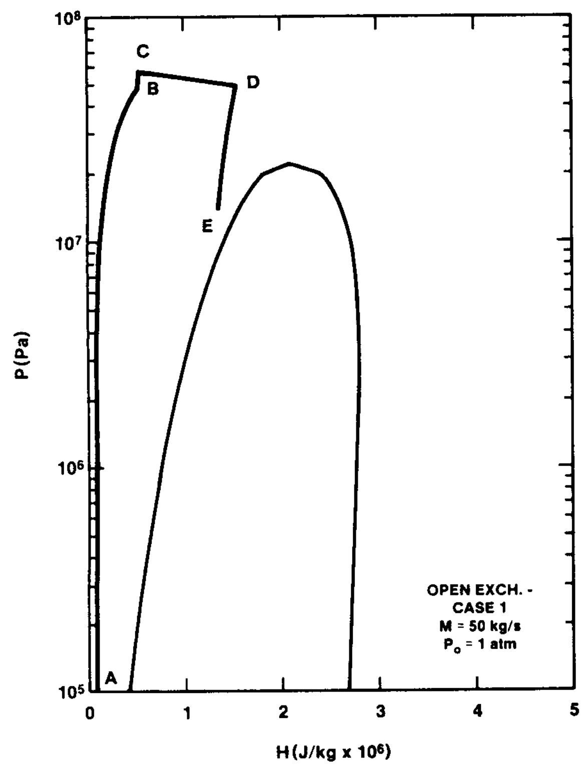

Figure 8. Pressure-enthalpy characteristics for M=50 kg/s; open heat exchanger base case.

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 9 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 temperature increases rapidly and the cooling rate decreases. For increasing flow rates, the initial diameter increases, and the diameter decreases less rapidly, consistent with the increased rate of cooling. For optimum conditions, the average diameter is from 10 to 20 m.

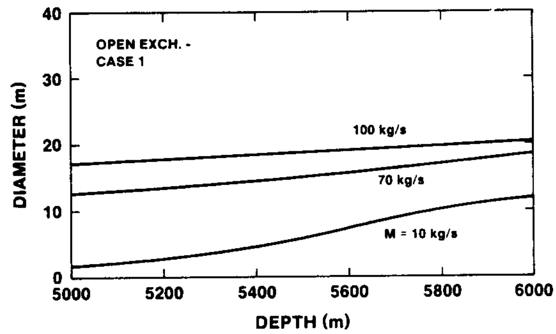

Figure 9. Open heat exchanger diameter for various flow rates; base case.

The optimum operating flow rate for the well is the flow that maximizes the rate at which thermal energy is extracted and converted to useful electric power. Following the approach of Hickox and Dunn (1985), we take the energy conversion efficiency as a first approximation to be the Carnot efficiency, given by:

$$\eta = 1 - \frac{T_{ambient}}{T_{well\ exit}} \qquad (7)$$

The net useful power is thus given by

$$Q_e = \eta\ Q_{thermal} \qquad (8)$$

Figure 10 shows the net useful power in MWe for a single well as a function of flow rate. Three cases are shown: (1) a closed heat exchanger consisting of closed concentric pipes surrounded by solidified magma, (2) an open heat exhanger which is assumed to operate with slug flow and the fully-developed heat transfer model discussed previously, and (3) an open heat exchanger in which the effective thermal conductivity has been taken as twice the nominal value used in the fully-developed model. This latter case represents to some degree the enhancements which may be possible due to entry length and buoyancy effects. An order of magnitude increase in the available power is found between the closed exchanger and the enhanced open exchanger. The open exchanger has a very broad optimum region in which a rate of 30 MWe net power is conservatively estimated. Reasonable enhancements may easily increase this rate by a factor of two or more.

SUMMARY

The open direct contact heat exchanger has the most promise for high rates of energy extraction from crustal magma bodies. The field experiments in the molten zone of Kilauea Iki lava lake demonstrated the validity of this concept at shallow depth and showed that very high rates of energy extraction could be achieved.

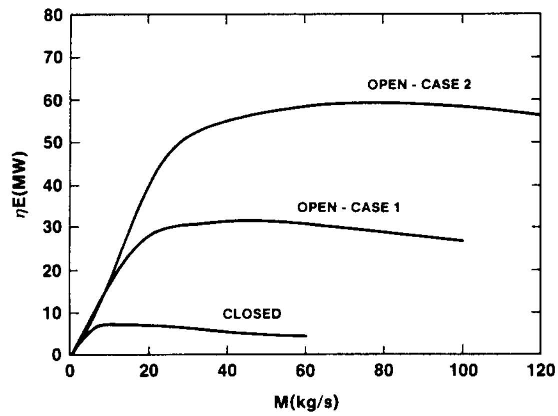

Figure 10. Net converted power for a single heat exchanger.

Experimental and analytical studies show that thermal-stress fracturing will occur in a solidifying magma around a cooled borehole. We predict that large primary fractures will propagate from initial micro-fractures in a glass phase, and that secondary interconnecting fractures will arise under the combined influence of fracture wall cooling, hydraulic pressure within the fracture, and weak inter-granular boundaries in the crystalline phases. Current estimates of the extent of fracturing lead to permeabilities which favor the flow of heat exchange fluid through the medium.

Numerical simulation of the energy extraction process from a single well open heat exchanger elucidates several important features. For expected well depths, the fluid pressure in the heat exchanger will be well in excess of the critical pressure of water. Because of the large flow area, heat transfer to the fluid will occur essentially isobarically but with substantial volumetric expansion. The resulting density imbalance between the injection and return flow paths will allow the well to self-flow as an open thermo-syphon with the flow rate limited only by the wellhead pressure. In all cases currently anticipated, neither flashing to two-phase flow nor two-phase choking will occur as is commonly the case in vapor producing geothermal wells. The extent of solidification and fracturing of the magma is greatly dependent on the rate of cooling. Our estimates show that magma can be solidified to a diameter on the order of 20 m, resulting in net energy extraction rates of 30 MWe. Reasonable enhancements due to secondary effects not included in the conservative analysis are expected to increase this rate by a factor of two or more.

The ultimate tests of magma energy extraction processes will be carried out by drilling into an active crustal magma body. The current experimental and analytical investigations will guide the planning of these field experiments and be used for data interpretation and evaluation.

REFERENCES

Carslaw, H. S. and Jaeger, J. C. (1959), Conduction of Heat in Solids, 2nd edition, Clarendon Press, Oxford.

Carson, C. C. and Haraden, J. (1985), The Economics of Magma Power Generation, GRC Trans., Vol. 9, Part I, pp. 171-175.

Colp, J. L. (1982), Final Report - Magma Energy Research Project, Sandia Report SAND82-2377, Sandia National Laboratories, Albuquerque, NM 87185.

Dunn, J. C. (1983), Energy Extraction from Crustal Magma Bodies, ASME/JSME Thermal Engineering Joint Conference Proceedings, Vol. II, pp. 93-100.

Dunn, J. C., Carrigan, C. R., and Wemple, R. P. (1983), Heat Transfer in Magma in Situ, Science, V. 12, pp. 3-8.

Gartling, D. K. and Hickox, C. E. (1982), MARIAH-A Finite Element Computer Program for Incompressible Porous Flow Problems, Sandia Natl. Labs. Report SAND-1623, Albuquerque, NM.

Hardee, H. C. (1981), Convective Heat Extraction From Molten Magma, J. Volcanol. Geotherm. Res., V. 10, p. 175-193.

Hardee, H. C., Dunn, J. C., Hills, R. G., and Ward, R. W. (1981), Probing the Melt Zone of Kilauea Iki Lava Lake, Kilauea Volcano, Hawaii, Geophy. Res. Lett., V. 8, pp. 1211-1214.

Hickox, C. E. and Dunn, J. C. (1985), Preliminary Considerations for Extraction of Thermal Energy from Magma, GRC Trans., V. 9, Part II, pp. 319-324.

Ramey, H. J. (1962), Wellbore Heat Transmission, J. Petr. Tech., April, pp. 427-435.