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CONVECTIVE HEAT TRANSPORT IN GEOTHERMAL SYSTEMS

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ABSTRACT

Most geothermal systems under exploitation for direct use or electrical power production are of the hydrothermal type, where heat is transferred essentially by convection in the reservoir, conduction being secondary. In geothermal systems, buoyancy effects are generally important, but often the fluid and heat flow patterns are largely controlled by geologic features (e.g., faults, fractures, continuity of layers) and location of recharge and discharge zones. During exploitation, these flow patterns can drastically change in response to pressure and temperature declines, and changes in recharge/discharge patterns.

Convective circulation models of several geothermal systems, before and after start of fluid production, are described, with emphasis on different characteristics of the systems and the effects of exploitation on their evolution. Convective heat transport in geothermal fields is discussed, taking into consideration (1) major geologic features; (2) temperature-dependent rock and fluid properties; (3) fracture- versus porous-medium characteristics; (4) single- versus two-phase reservoir systems; and (5) the presence of noncondensible gases.
INTRODUCTION

To date, hydrothermal convection systems are the only geothermal systems that have been developed commercially. For geopressed, hot dry rock, and magma type of geothermal resources the economics are uncertain, and the technology has only started to be developed.

In most hydrothermal systems liquid water, contained in the pores and fractures of the rocks, is the predominant fluid that controls the vertical pressure gradient. These are the so-called liquid-dominated systems. In a few fields this pressure gradient is controlled by the vapor phase (e.g., The Geysers, USA; Larderello, Italy; Kamojang, Indonesia; Matsukawa, Japan); these systems are referred to as vapor dominated.

In the hydrothermal systems convection is the main mode of heat transport in the reservoir. However, conduction is the dominant heat transfer mechanism in the less permeable overlying caprock and underlying bedrock.

Under natural (pre-exploitation) conditions hydrothermal reservoirs are not static like oil and gas reservoirs but are dynamic in nature (Donaldson et al., 1983). The distribution of temperatures, pressures, and fluids is controlled by natural convection, which could be dominantly free or forced. That is, the fluid flow patterns are determined primarily either by the buoyant effect of the heated fluid or by external forces (i.e., location of heat/mass sources and sinks). The overall movement of geothermal fluids in the reservoir is driven by natural pressure gradients; however, the circulation patterns may be controlled by geologic features, such as faults, zones or layers of differing permeability, and multiphase zones.

With exploitation a number of changes occur in the reservoir. There are changes in temperature, pressure, and composition of the fluids and in stresses in the rock mass. In addition, locally high pressure and temperature gradients are formed around the
production and injection wells (in single-phase reservoirs the temperature gradient near production wells is generally small). Changes in the pattern of heat and mass (convective) transport tend to reflect the production and injection scheme used in the field. In other words, forced convection becomes, or continues to be, predominant in the reservoir.

As a result of fluid production and injection various phenomena can occur in the reservoir. In this paper we will discuss these phenomena and the evolution of geothermal systems in response to their exploitation, giving special emphasis to the changes in convective patterns within the reservoir.

**MAIN PROCESSES OCCURRING IN THE RESERVOIR**

Since the reservoir is a dynamic system it presents a continuous movement of fluids (liquid, steam, gases) that is controlled by the pressure gradient, the effective permeability of the rocks, and the viscosity and density of the fluids, as described by Darcy's law. Simultaneously there is transfer of heat, mainly by convection. While conduction occurs in response to thermal gradients, convection is directly related to fluid movement.

Boiling and condensation in the geothermal reservoir have very important effects because of the significant difference in steam and liquid water enthalpies (At 250°C the latent heat of vaporization is about 1,700 kJ/kg). During these processes the rock mass acts as a buffer. It transfers heat to the fluid during boiling and absorbs heat during condensation.

In many two-phase geothermal systems a counterflow of steam and liquid, caused by density differences, is observed (Fig. 1). This convective process is a very effective heat transfer mechanism that is strongly controlled by the vertical permeability of the reservoir formation (Bodvarsson et al., 1982). When fluids are produced from the bottom of these reservoirs the pressure at the upper part could increase as a result of steam
upflow from depth and condensation in the shallow regions. The condensation causes a
temperature rise and consequently a pressure increase.

Under this lower-zone production scheme, and if the vertical permeability is high
enough, the pressure at the bottom of the reservoir could stabilize because a constant
pressure region exists at the top of the system. Bodvarsson and Cox (1986) show that
the fluid depletion occurs primarily at the top of the reservoir, where a steam-dominated
zone develops that is recharged by lateral steam flow. Apparently during production
from the bottom layer, the pressure declines until it induces significant vertical recharge,
and gravity drainage becomes the dominating flow mechanism, with an expanding steam
zone at the top of the reservoir. Little localized boiling occurs in this upper zone, so that
temperatures (and pressures) are maintained (Fig. 2).

Boiling and condensation also affect the general transport of fluids in the reservoir
and that of dissolved solids and gases. Changes in steam saturation cause the effective
permeability of the reservoir rocks to change (relative permeability effects). Phase
changes also alter chemical equilibria, resulting in the dissolution or precipitation of
minerals in the reservoir pores and fractures, thus increasing or decreasing the rock per­
meability. The amount of noncondensible gases in the liquid and gaseous phase is also
controlled by boiling and condensation.

Another process often observed in geothermal systems is the mixing of fluids of
differing characteristics as a result of natural recharge and/or injection/production
operations. Changes in temperature, saturation, and chemical composition of the reser­
voir fluids can be the result of mixing; such changes can in turn cause chemical reactions
between the fluids and the reservoir rocks.

Production reduces pore pressure in the reservoir rocks and increases the effective
stress on the rock grains. Thus it may eventually result in the consolidation of the
reservoir formation at depth and cause ground deformation at the surface.
The thermal contraction of reservoir rocks in response to the influx of colder waters or to the lowering of pressures in two-phase boiling systems can produce microfracturing of the rock and thus increase its permeability. There are other processes acting in the system, such as capillary pressure effects, osmosis and adsorption, but their effects on reservoir behavior are generally not believed to be significant.

Another phenomenon that can occur with the exploitation of a geothermal system is the change in well production characteristics. It could be related to changes in the reservoir, such as boiling, steam segregation, or shifts in recharge patterns. However, the changes observed at the wellhead could be only a function of well behavior. For example, by lowering the wellhead pressure, thus increasing production, and decreasing the pressure in the borehole, zones that were not contributing fluids might begin feeding the well. This will result in fluid mixing in the borehole and possible changes in the temperature and chemistry of the produced fluids. In some instances scaling might occur, reducing the effective diameter of the well and increasing pressure losses.

These are only a few examples of the complex processes and changes that might occur in geothermal reservoirs and wells in response to exploitation. It was indicated that the variation in parameters measured at the wellhead could be the result of complex reservoir processes or well operation methods. Thus, to predict the future behavior of a geothermal field under a given development plan, it will be difficult to extrapolate values measured during the early evaluation phase of the resource. During that initial period only limited changes might occur in the system. With large-scale development quite different processes might be active in the reservoir and in the wells. All these processes and the geologic complexities associated with a geothermal system can be taken into account only by using numerical simulation techniques, as discussed by Bodvarsson et al. (this volume).

To illustrate the processes and changes discussed above we will describe the evolution of three liquid-dominated geothermal systems in response to exploitation. These
are: Cerro Prieto (Mexico), Wairakei (New Zealand), and Svartsengi (Iceland). Vapor-dominated systems will not be discussed because their behavior under production have not been extensively documented. There are still unanswered questions about their genesis and dynamics. Published data have been restricted to changes in the chemistry of the produced steam and to partial information on pressure and temperature distribution before and during field exploitation.

CERRO PRIETO

The Cerro Prieto geothermal system, Mexico, is located in the heterogeneous sedimentary fill of the Mexicali Valley. Wells, some exceeding 4,000 m depth, have identified a number of reservoirs interconnected through faults and permeable layers (Fig. 3).

The temperatures of the producing zones vary; temperatures above 350 °C have been measured in the field. The distribution of isotherms reflect the natural movement of geothermal fluids in the subsurface (Figs. 3 and 4). Before large-scale fluid production began, the hot fluids from a deep source located in the eastern regions of the system tended to ascend toward shallower zones as they flowed west. At the western edge of the field part of the geothermal fluid reached the surface as evidenced by the abundant hot springs and mud pots and volcanoes. Under natural conditions compressed liquid was present in most parts of the field. Only in the western part of the system might a two-phase zone have existed (Lippmann and Bodvarsson, 1983).

The permeability of the reservoirs generally varies between 20 and 50 md, and their transmissivity between 2 and 40 darcy-meters. The permeability of the producing zones is predominantly controlled by primary and secondary pores. Fracture permeability appears to be more significant in the deeper and hotter eastern reservoirs.

The exploitation of Cerro Prieto began in 1973. Initially fluid production was restricted to the wells drilled in the western part of the field, completed between 1,000 and 1,500 m depth. After 1980 deeper wells drilled in the central and eastern areas started
to supply significant amounts of fluids to the power plant (Lippmann and Mañón, 1986). Large quantities of fluids have been extracted from the field, changing the conditions and processes in the reservoirs.

The pressure in the shallow alpha reservoir (only found west of the railroad tracks shown on Fig. 4) declined by about 23 bars between June 1973 and December 1979 (Bermejo et al., 1979). For the same period the temperature drop was less than 10°C (Lippmann and Mañón, 1986). No data have been published on the changes in the deeper (below 1,500 m depth) reservoirs.

Most Cerro Prieto wells produce from a single-phase liquid zone. There is local boiling close to many of the wells, because of the strong recharge of colder waters from shallow aquifers and from the western edge of the field (Fig. 5); no extensive boiling zone has developed in the alpha reservoir in response to fluid production. Initially boiling around the wells produces an excess in flowing enthalpy, which later diminishes or disappears as the boiling front stabilizes (Grant et al., 1984; Truesdell et al., 1984). Boiling, as reflected by a silica deficiency in the produced fluids, causes mineral precipitation around the wells, possibly reducing the permeability of the reservoir and the productivity of the wells.

The strong cold water recharge is inferred from physical and geochemical data, such as the reduction in chloride content in the produced fluids (Fig. 6). A plot of enthalpy versus chloride content suggests the existence of “cold sweep” in the alpha reservoir in response to exploitation (Grant et al., 1984). The time of detection of “chloride breakthrough” in the western wells clearly indicates cold fluid recharge to this reservoir down a normal fault (Figs. 7 and 8). The temperature decline is retarded by heat conduction from the reservoir rocks. The hot influx from the east does not appear to change significantly with exploitation. The rate of recharge from the east seems to be limited by the presence of the two-phase zone located to the east of the alpha reservoir (Fig. 8). The associated fluid mobility decrease due to relative permeability effects
restricts the mass recharge from the deeper parts of the geothermal system (Lippmann and Bodvarsson, 1983; Truesdell and Lippmann, 1986).

Comparison of Figures 3 and 8 shows the changes in convective pattern in the western part of Cerro Prieto due to exploitation. One should add that the discharge of the surface manifestations along the western edge of the field has substantially decreased, again reflecting the pressure drawdown in the reservoir.

The behavior of the deeper reservoirs is not as well understood. Because of their more restricted recharge, the pressure drop and boiling in these zones might be stronger than in the alpha reservoir. This could result in more extensive mineral precipitation in the producing horizons, reducing well productivities.

The average enthalpy (mass weighted) of the produced fluids has also changed significantly with time. The enthalpy rise is related initially to the excess steam produced by some of the wells and later to the introduction of deeper, higher-temperature wells. Observed decreases in enthalpy seem to be due to the influx of colder recharge fluids.

Ground surface deformations have been measured in the Cerro Prieto area. However, it is not clear how much is due to natural seismic effects and how much to exploitation of the field. More details about the changes detected in this system are discussed by Grant et al. (1984), Truesdell et al. (1984), and Lippmann and Mañón (1986).

WAIRAKEI

A significant portion of the data discussed in this section was obtained from Grant et al. (1982).

The Wairakei field on the North Island of New Zealand began generating electricity in 1959. The producing horizons are at about 500 m depth, generally associated with a contact between a volcanic breccia and an ignimbrite. These zones tend to have high horizontal permeabilities; the permeability-thickness product for the reservoir tends to
vary between 10 and 100 darcy-meters. Its initial base temperature was about 260 °C. Before large-scale fluid production there existed a boiling zone that did not extend below 400 m depth.

In response to exploitation and the resulting pressure drawdown, the two-phase zone expanded downward. The upper part of this zone became vapor dominated, while the lower part remained liquid dominated. Figure 9 illustrates the changes observed in the reservoir.

The lack of pressure stabilization in the two-phase zone, as discussed in an earlier section (Main Processes Occurring in the Reservoir), is the result of the interference between producing wells. The overlap of their zones of influence does not allow the lateral recharge of steam that would maintain the pressure in this upper zone.

As fluid extraction continued, the size and vapor saturation of the steam zone kept increasing. In 1960 there was a tendency toward an increase in the flowing enthalpy of the produced fluids; most wells showed excess steam. At that time the water columns in the wells tended to disappear, and internal fluid flow within the wells between different feed zones became common (Grant et al., 1982).

In 1962 the behavior of the field stabilized. Some wells feeding from shallow zones continued to show an increase in flowing enthalpy, eventually producing superheated steam. However, in most wells the enthalpy kept declining, finally reaching nearly that of liquid water. The pressure profile in the reservoir clearly indicated the existence of a vapor-dominated zone overlying a liquid-dominated region. More than 95% of the produced fluid originated from this lower region.

As a result of the reservoir pressure reduction, there has been significant ground subsidence at Wairakei. The largest surface deformations, contrary to expectations, are outside the wellfield (Fig. 10). It is postulated that this may be explained by the presence of highly compressible pumice breccia in the area of maximum subsidence (Allis, 1982b).
Presently the Wairakei reservoir is being recharged by deep hot waters and by
colder shallow groundwaters. Since 1966 the mass extracted from the system has almost
totally replaced by natural recharge (Grant et al., 1982).

The pressure reduction in Wairakei has caused considerable hydrologic and geo-
chemical changes in the nearby Tauhara geothermal system, about 6 km to the
southeast (Allis, 1982a; Henley and Stewart, 1983). Figure 11 compares the fluid move-
ment and characteristics within the system in 1962 and 1978.

In 1962 (under natural state conditions) hot springs discharged deep chloride waters
along the margins of the Tauhara system. Steam rising from a deep two-phase system
generated sulfate-bicarbonated waters by absorption in shallow groundwater and
chloride-sulfate waters by mixing with chloride water.

During 1978-1981, as a result of pressure reduction related to Wairakei production,
the chloride springs along the western flanks of Tauhara had disappeared. In addition
the upflow of steam had increased 5 to 10 times, substantially increasing the volume and
temperature of the steam-heated waters (Henley and Stewart, 1983). As shown schemati-
cally in Figure 11, exploitation of the nearby Wairakei field changed substantially the
convective and chemical characteristics of the Tauhara geothermal system.

SVARTSENGI

The Svartsengi geothermal field is located in southwest Iceland. Eleven wells have
identified a high temperature reservoir (240°C) below 600 m depth. The geothermal
fluids are used to heat fresh water that is piped to nearby towns for space heating. In
addition, some of the produced fluids are used for generating 8 MW of electricity (Eliass-
son et al., 1977; Kjaran et al., 1980; Gudmundsson et al., 1984)

The wellfield covers an area of about 0.6 km² (Gudmundsson et al., 1984). Geophy-
sical surveys have shown a resistivity low (less than 5 ohm-m) over a region of about 7
km². In the subsurface one encounters basalt flows and basalt hyaloclastites.
Permeability is primarily associated with contacts between flows, fractures, and intrusives; intrusives are common below 800 m depth (Franzson, 1983).

A conceptual (natural state) model of the Svartsengi field has been developed by Eliasson et al. (1977), Kjaran et al. (1980), and Regalado (1981). They postulate that the system is recharged by rainfall from a mountainous area some 20 km to the east. The water percolates to about 3 km depth and is heated as it flows west. The fluids ascend in the Svartsengi area because of buoyancy, developing a convection cell (Fig. 12). This explains the near isothermal conditions in the reservoir. According to Regalado (1981) the upflow zone could be confined to a major near-vertical fault located near wells 2, 3, and 10. A small boiling zone is inferred to exist between 200 and 400 m in the vicinity of this fault. Counterflow of steam and liquid water occurs in this two-phase region (Fig. 12).

A caprock between 300 to 500 m depth, formed by hydrothermal alteration, hinders further fluid ascent. Most fluids spread laterally below the caprock, cool by conductive heat losses, and descend. Some of the upflow fluids recharge aquifers in shallow regions. This and the presence of the two-phase zone strongly suggests that the caprock is leaky, perhaps because of the presence of near-vertical faults. The reservoir is believed to extend to about 2,500 m depth, bounded below by a low-permeability bedrock.

Numerical modeling studies (Bodvarsson, 1986) indicate that the reservoir has a 0.5 to 1.0 km-radius high-mobility inner zone surrounded by a low-mobility outer zone. The contrasting mobility could be due to temperature effects on the fluid properties rather than permeability changes. (The permeability could be about 85 md throughout the field.) On the basis of resistivity data Kjaran et al. (1980) estimated a temperature of 41 °C outside the geothermal anomaly and at reservoir depth, giving some credence to the composite model. Bodvarsson’s results indicate that the reservoir transmissivity is about 35 darcy-meters.
Fluid production started in 1976; by early 1983 the pressure decline in the reservoir was between 8 and 9 bars. Bodvarsson (1986) suggest that about 25% of the fluids recharging the field comes from the two-phase zone. With exploitation the counterflow of steam and water in this zone has increased. Because more steam is condensating there now, the temperature has increased in shallow regions of the field. The larger upflow of steam is manifested by steaming grounds that now are common at Svartsengi. Before 1976 steam was visible only during very cold days.

FINAL REMARKS

With the purpose of illustrating the complexity and variability of geothermal systems, the main characteristics, processes, and changes observed in three liquid-dominated fields have been described. Evidently there is no general purpose model that could be applied to these hydrothermal convective systems. Each has particular features that will have to be considered when predicting their future behavior under exploitation.

However, only a few complexities have been discussed. The three systems described in this paper do not include fluids with high concentrations of dissolved solids or noncondensible gases. Brines with higher concentrations of these constituents not only make it more difficult to handle the fluids at the surface, but also add complexities to the processes occurring in the geothermal reservoir. For example, higher salinities increase the boiling and critical points of the geothermal brines and increase the solubility of calcite. High concentrations of noncondensible gases alter the boiling curve of liquid water significantly and tend to expand two-phase zones in geothermal systems (O'Sullivan et al., 1985).

The changes in a geothermal system in response to fluid production are the result of coupled physical and chemical processes, most of them highly nonlinear. The complexity of these phenomena, and that of the geologic structures controlling the heat and mass transport in the hydrothermal convective systems, requires the use of mathematical
tools to simulate and predict their behavior under given reservoir management plans. Mathematical models of increasing sophistication could be applied to the study of these systems if an adequate data set were available. If the information is only scarce, simpler models could be applied, as discussed in an accompanying paper in this volume (Bodvarsson et al., 1986).

As more complete field data sets become available it will be possible to validate the conceptual models being developed for individual hydrothermal systems. A carefully designed monitoring program, including geochemical and reservoir engineering measurements, will be necessary to obtain the required information. Mathematical models, especially numerical computer codes, could then be used to establish the importance of given reservoir processes in the geothermal system and develop a conceptual model that reflects the data measured in the field. The next step would be to evaluate several fluid production/injection scenarios and to establish the reservoir management plan that optimizes the recovery of the heat stored in the subsurface.
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REFERENCES


FIGURE CAPTIONS

Figure 1. Schematic model of liquid-steam counterflow in a two-phase geothermal reservoir (from Bodvarsson and Cox, 1986).

Figure 2. Schematic model of flow patterns and depletion mechanisms for a well producing from a deep zone in a two-phase geothermal reservoir (from Bodvarsson and Cox, 1986).

Figure 3. Hydrogeologic model of the Cerro Prieto field. Arrows indicate direction of geothermal fluid flow under natural conditions; lines indicate temperature profiles (the points corresponding to 300°C are located below the respective wells). The parts of the temperature profiles shown by heavy lines indicate temperatures of 300°C or greater (from Halfman et al., 1986).

Figure 4. Cerro Prieto. Depth to the 300°C isotherm (from Lippmann and Mañón, 1986).

Figure 5. Schematic section across the western Cerro Prieto reservoir showing flows of hot (stippled) and cold water toward the producing wells, the chemical and thermal fronts, and zones of near well boiling (from Grant et al., 1984).

Figure 6. History of Cerro Prieto well M-35 showing chemical and thermal breakthrough (from Truesdell and Lippmann, 1986).

Figure 7. Chloride breakthrough in Cerro Prieto wells that were in line before 1979 (from Truesdell and Lippmann, 1986).

Figure 8. Postulated fluid recharge pattern in the Cerro Prieto alpha reservoir resulting from its exploitation (from Truesdell and Lippmann, 1986).

Figure 9. Section through the Wairakei reservoir in its natural state and in 1972 (from Grant et al., 1982).

Figure 10. Total subsidence (in meters) at Wairakei, 1964-1974 (from Stilwell et al., 1976).

Figure 11. Schematic models showing features of the Tauhara geothermal system in 1962 and 1978 (from Henley and Stewart, 1983).
Figure 12. Plausible conceptual model of the Svartsengi geothermal system showing steam-liquid counterflow in the two-phase zone overlying a liquid reservoir (from Bodvarsson, 1986)
Fig. 1

- Ground Surface
- Heat Loss
- Upper Production Zone
- Lower Production Zone
- Heat Gain
- Steam Flow
- Liquid Flow
- Two-phase Conditions

Q
Cerro Prieto
Depth (in meters) to the 300°C Isotherm

Fig. 4
Fig. 6
CERRO PRIETO
WELLS ON LINE BEFORE 1979

Chloride Breakthrough
* Before 1978
● Between 1978 and 1982
○ Not Evident by 1984

Fig. 7
Fig. 9
Total subsidence at Wairakei, 1964 to 1974.

Fig. 10
Fig. 11

(a) 1962

(b) 1978

Fig. 11
Fig. 12
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