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Numerical Studies of Gravity Effects in Two-Phase Reservoirs

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ABSTRACT

Numerical studies are performed to investigate the effects of localized feed zones on the pressure transients in two-phase reservoirs. It is shown that gravity effects can significantly affect the pressure transients, because of the large difference in the density of liquid water and vapor. Pressure transients for shallow and deep feed zones and the resulting fluid flow patterns are discussed.

INTRODUCTION

Conventional analysis of pressure transient data from geothermal reservoirs generally neglects gravity effects. In the case of single-phase reservoirs this assumption may be reasonable, except where vertical temperature gradients within the reservoir are large. For two-phase reservoirs this approximation can cause large errors in the analysis because of the large density difference between vapor and liquid water. This density difference gives rise to counterflow of vapor and liquid (Martin et al., 1975), with vapor moving upwards and liquid percolating downwards. Associated with the counterflow is strong heat transport resulting from the large differences in the enthalpy of vapor and liquid water.

Another common problem in the analysis of pressure transient data from geothermal reservoirs is localized fluid production, since most wells have only a few major feed zones. A similar problem has been addressed in the oil and gas and groundwater literature in terms of partial penetration of wells (Earlougher, 1977; Witherspoon et al., 1967). The applicability of the available solutions however, is limited because they are based on the assumption that the production interval is at the top of the reservoir and that gravity effects are negligible. Thus, there is an apparent need to investigate pressure transients in geothermal wells with localized feed zones, especially for two-phase reservoirs.

Studies of pressure transients in two-phase geothermal systems are rather scarce. Various investigators have extended the single-layer pressure transient theory to two-phase systems (Grant, 1978; Garg, 1978; O'Sullivan, 1980; Sorey et al., 1980). These investigators incorporated the effects of the fluid enthalpy in their methods of analysis, but rigorous analysis is still not possible due to lack of knowledge regarding relative permeabilities (Grant, 1980). Moench (1978) and Moench and Atkinson (1978) investigated pressure transients in two-phase fractured reservoirs with immobile liquid water. Cox and Bodvarsson (1985) investigated the effects of localized two-phase zones on pressure transient data. They included gravity effects in some of the cases and illustrated that they can have large effects on the pressure transients.

The main objective of this paper is to investigate the importance of gravity effects and localized fluid production (partial penetration) on the pressure behavior of two-phase reservoirs. Of particular interest is the pressure transient behavior of observation wells with feed zones at different depths in the reservoir, and the overall fluid flow patterns in such systems.

APPROACH

The reservoir system considered is shown in Figure 1. There is a single well penetrating a two-phase reservoir; production from the well is assumed to be either at the top or bottom of the reservoir. The reservoir is 500 m thick and the production interval is assumed to be 50 m thick. A ten-layer grid is used, each layer being 50 m thick. A constant mass flow rate of 15 kg/s is specified for the well.

Initially, two-phase conditions prevail everywhere in the reservoir system. Two-phase conditions with nearly uniform vapor saturation ($S_v \approx 0.05$) were achieved by maintaining an appropriate heat flow through the system (Martin et al., 1976). Constant heat flux is applied at the bottom and the energy is transferred to the top of the reservoir by liquid-vapor counterflow. A constant heat sink is specified at the top of the reservoir, representing conductive heat losses. The heat flux used was 0.4 W/m^2, which resulted in a vapor liquid counterflow of approximately 2.4 x 10^{-7} kg/s m^2. The initial pressure is practically hydrostatic with depth, and the initial temperature in the top and bottom layers is 245 and 287 °C.

A porous-medium model is employed in this work, as it appears reasonable to attempt to understand porous medium behavior before tackling the more complex case of a fractured reservoir. The porosity and horizontal permeability in the system are assumed to be 5% and 50 md, respectively; the vertical permeability is varied in the simulations. Linear relative permeabilities with immobile liquid saturation of 0.40 and immobile vapor saturation of 0.05 are used. The numerical simulator MULKOM (Pruess, 1982) is used in this work.

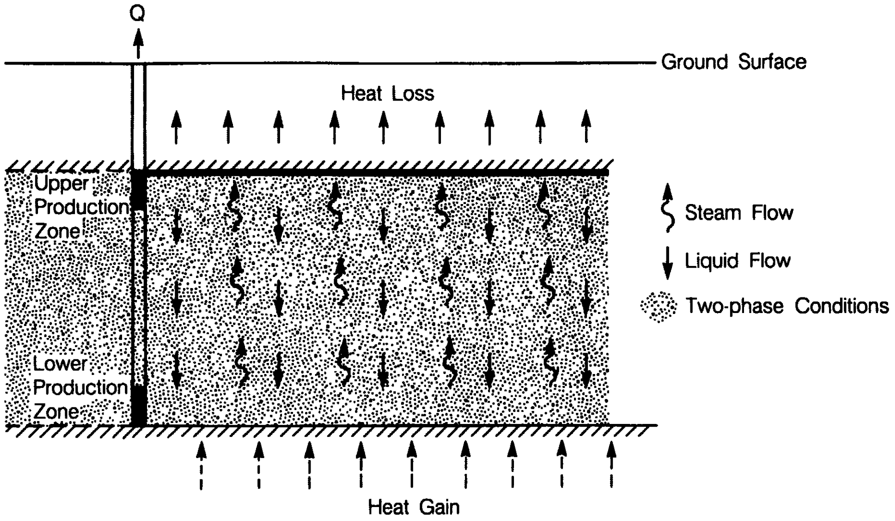

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Figure 1. Basic model used in the simulation studies. A stable two-phase zone is achieved by heat flow through the reservoir.

PRODUCTION FROM DEEP FEED ZONES

A number of cases are simulated with fluids produced from the bottom 50 m of the reservoir. Figure 2 shows the simulated pressure transient results at the well for various vertical permeabilities of the reservoir rocks. The figure shows, as expected, that the lower the vertical permeability the larger the pressure decline. The pressure decline is near-linear at early times and the slope of the line can be used to calculate the permeability-thickness of the producing layer, providing that proper enthalpy corrections are made (Grant, 1980). At later times the pressure decline stabilizes, as fluids from above recharge the producing layer. This is similar to typical pressure transient data from leaky aquifers (Hantush, 1960). However, the subsequent rise in pressure is not consistent with leaky aquifer solutions, but can be explained by transients in the enthalpy of the produced fluids shown in Figure 3. Figure 3 shows that after an initial stabilization in the flowing enthalpy at about 1500 kJ/kg, it decreases again to about 1250 kJ/kg, which is practically the liquid enthalpy corresponding to the initial temperature of the producing layer (287 °C). The decrease in enthalpy is due to liquid recharge from above; the near hydrostatic pressure gradient in the system does not allow downward flow of vapor. This in turn causes an increase in pressure at the well because an increase in the liquid fraction of the flowing fluids enhances the overall mobility of the mixture.

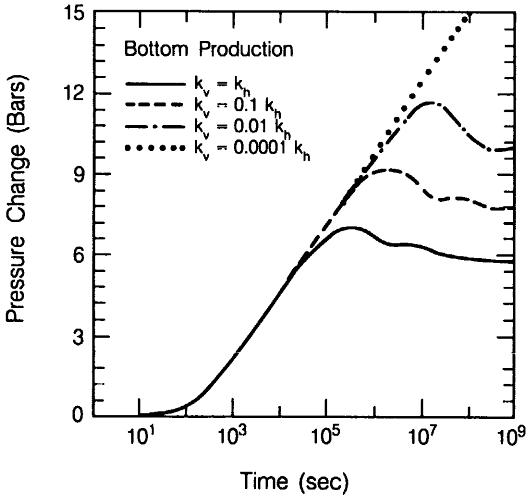

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Figure 2. Pressure decline at the well, when fluids are produced from a deep feed zone. Different vertical permeabilities are used.

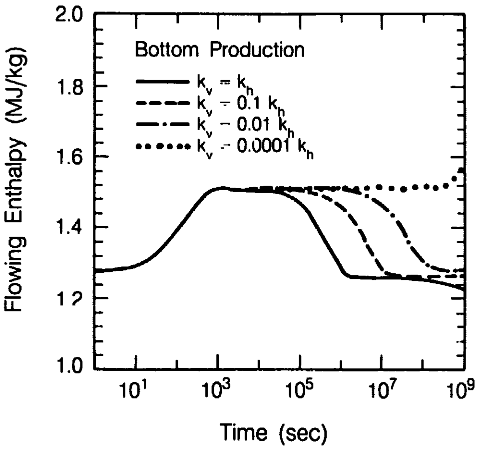

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Figure 3. Flowing enthalpy of the produced fluids for deep production and various values of the vertical permeability.

Log-log plots of the pressure transients at various observation points in the producing layer are shown in Figure 4 for the case of isotropic permeabilities. The curves show similar characteristics to those observed at the well and much more pressure stabilization than could be explained using a leaky aquifer solution. The characteristic shape of the curves closely resembles those obtained for a system with a constant pressure zone. However, evaluation of the pressure transients using such models will yield erroneous estimates for the hydrological parameters of the system.

The pressure transients for observation points at the top of the reservoir system exhibit more unorthodox behavior, as shown in Figure 5. Pressure transient data are given for observation wells located at different radial distances from the producing well. Figure 5 shows that the pressure actually increases at the top of the reservoir due to steam upflow from depth and condensation in the shallow regions. The condensation causes a temperature rise and consequently a pressure increase. The shorter the distance between the producing well and the observation point, the more pronounced the pressure rise. The pressure rise certainly also depends upon the effective vertical permeability of the vapor phase as well as the production rate of the well. The data shown in Figure 5 are for the case of isotropic permeability, but pressure increases are also observed for the cases with an anisotropy of 10 and 100. Here anisotropy is defined as the ratio of horizontal to vertical permeability. Pressure increases in shallow two-phase zones due to deeper production have been observed in several geothermal fields, for example, the Svartsengi geothermal field in Iceland (V. Stefansson, personal communication, 1982).

The pressure transient data shown in Figure 5 illustrate that very little if any pressure decline is observed at the top of the reservoir system during the entire time modeled (30 years). Thus, the pressure stabilization seen at the observation points at the bottom of the reservoir (Fig. 4) can be explained by the constant pressure zone at the top of the reservoir system. In order to explain the lack of pressure drawdown at the top of the reservoir one must consider the depletion patterns that evolve during production. Figure 6 shows the vapor saturation distribution in the system at the end of the simulation period (30 years). The figure shows that the fluid depletion occurs primarily at the top of the reservoir, where a steam-dominated zone has developed. In the lower part of the reservoir, in the vicinity of the well, two-phase conditions have disappeared and only subcooled liquid is present. Farther from the well, the initial thermodynamic conditions prevail with vapor saturations close to 0.05. Apparently, during production from the bottom layer the pressure declines until it evokes significant vertical recharge, and gravity drainage becomes the dominating flow mechanism, with an expanding steam zone at the top of the reservoir system. Little localized boiling occurs at the top of the reservoir so that temperatures and consequently pressures are maintained. Lateral flow of steam in the vapor-dominated zone will also help maintain temperatures and pressures (Cox and Bodvarsson, 1986). However, one would expect that if a finer grid were used close to the top of the reservoir, a gradual pressure decline would occur. This possibility will be addressed in a subsequent study.

The development of the subcooled liquid zone (see Fig. 6) is also an interesting consequence of the flow patterns that develop in the system. Two-phase conditions disappear in this zone because of downward flow of cooler liquid water from shallower portions of the reservoir. Figure 7 shows the total temperature changes in the system after 30 years of production. Considerable cooling has occurred in the near region of the well (to a radial distance of about 300 m) due to the downward flow of cooler liquid water. It is only in the bottom layer (the producing layer) that a significant temperature drop due to boiling has occurred.

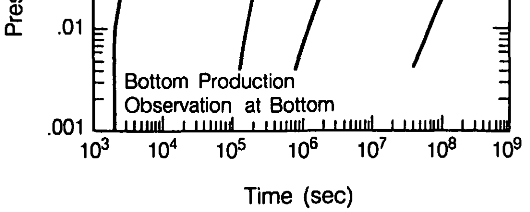

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Figure 4. Pressure transients in deep observation points at different radial distance from the well. fluids are produced from the deep feed zone.

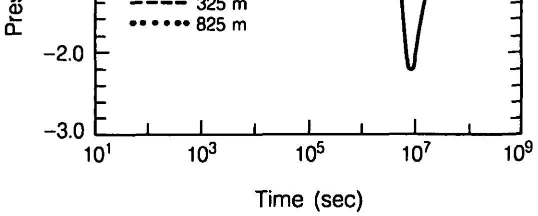

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Figure 5. Pressure transients at shallow observation points located at different radial distance from the well. Fluids are produced from the deep feed zone.

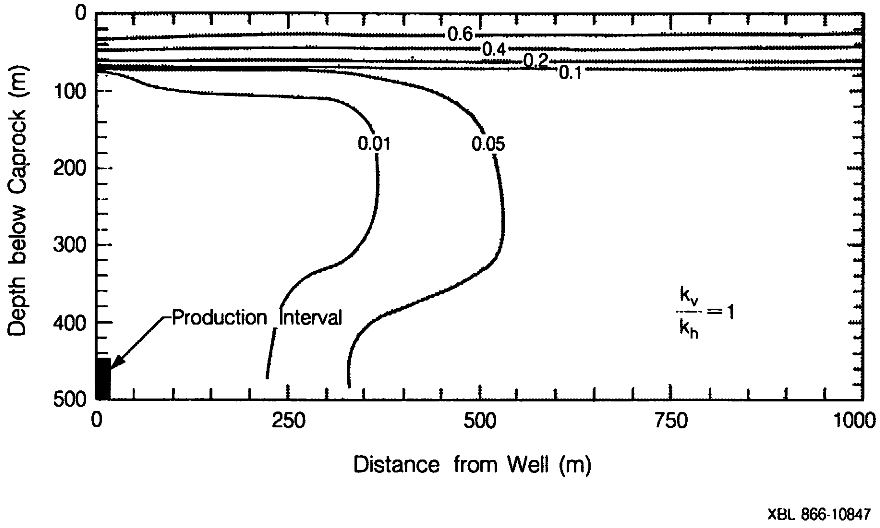

Figure 6. Vapor saturation contours at the end of the simulation (30 years) for the case of deep production and isotropic permeability.

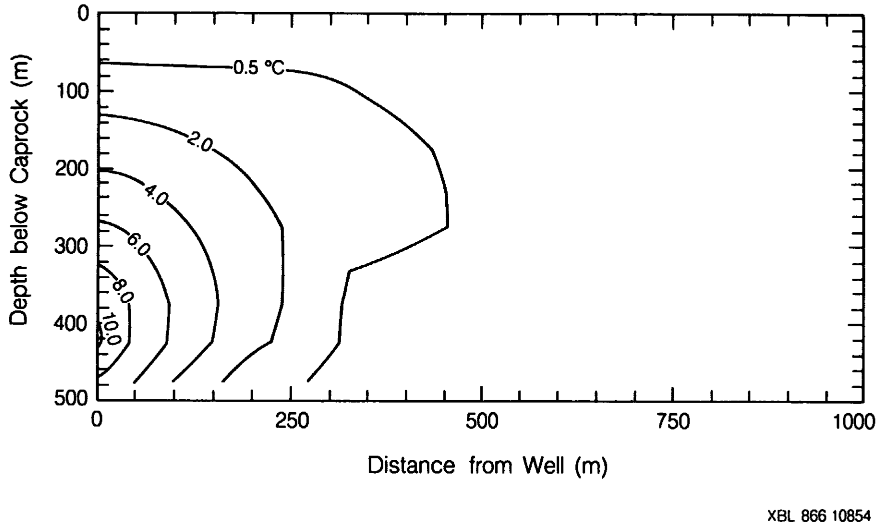

Figure 7. Total temperature changes in the system at the end of the simulation for the case of deep production and isotropic permeability.

It is of interest to investigate how the flow patterns change with decreasing vertical permeability, since one expects that for most geothermal systems the vertical permeability is considerably lower than the horizontal permeability. Figure 8 shows the distribution in vapor saturation for the same system, but with a vertical permeability ten times lower (anisotropy of 10). The results shows the same general trends as those obtained in the isotropic permeability case, or fluid depletion at shallow depths and the presence of a subcooled liquid zone. In this case, however, the vapor dominated zone and the subcooled liquid zone extend farther from the well (over a larger reservoir volume). The greater extent of these zones is caused by the larger pressure drop in this case (see Fig. 2), as a result of the lower vertical permeability.

Similar results were obtained for the case with anisotropy of 100, but when anisotropy was assumed to be 10^4, little vertical leakage occurred. All of the reservoir remains two-phase for the entire simulated period. Near the production interval significant boiling occurred and an expanding vapor-dominated zone formed.

In summary, Figure 9 shows the resulting model of fluid flow patterns and reservoir depletion for a well with a deep feed zone. It is assumed in the figure that there is sufficient vertical permeability to cause shallow reservoir depletion rather than a localized boiling zone around the well feed zone. The production rate and the anisotropy ratio determine the

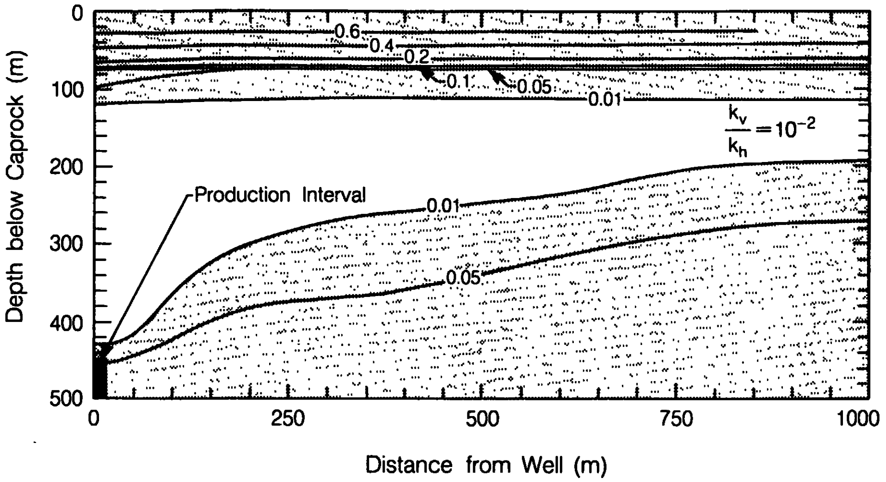

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Figure 8. Vapor saturation contours at the end of the simulation for the case of deep production and permeability anisotropy of 10.

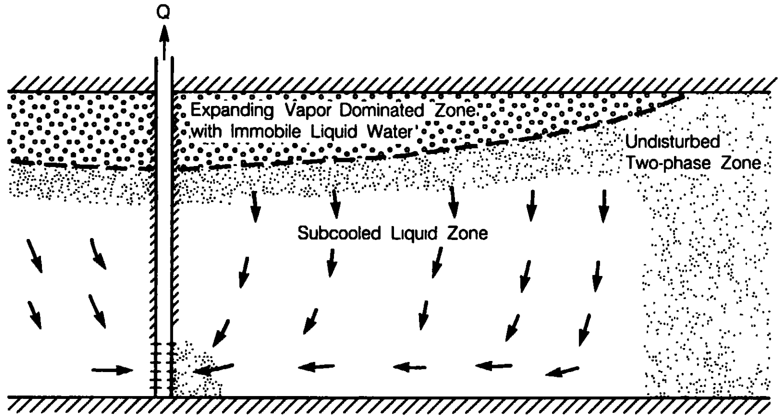

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Figure 9. Schematic model of flow patterns and depletion mechanisms for a well with a deep feed zone.

radius of influence for this system, and then gravity drainage provides a very efficient production (depletion) mechanism.

In the model shown in Figure 9, vertical flow is dominant, and one should therefore be able to estimate the average vertical permeability from pressure transient data for such systems. As mentioned before, the early pressure transients in the well and at nearby observation points can be used to determine the average horizontal transmissivity of the production layer. The later time pressure transient data are mostly affected by the vertical liquid flow and the development of the near-constant pressure vapor-dominated zone at the top of the system. Figure 10 shows the correlation between the stabilized well pressures and the anisotropy ratio.

As shown in the figure a log-linear correlation is obtained. Such a correlation between these parameters is expected for linear problems, but is rather surprising for this more complex non-linear problem. However, the fluids flowing in the reservoir system are predominately liquid water and gravity drainage rather than boiling causes the reservoir depletion. Hence, relative permeability effects are small.

It may also be possible to estimate the average vertical permeability of steam (kk_{rs}) from the pressure increase at shallow observation points (Fig. 4). This pressure increase is due to upflow of steam and condensation at the top of the reservoir system. The pressure change can be used to estimate the temperature change at the top of the reservoir, and the temperature change can in turn be used to infer the amount of steam that has condensed. Averaging the total amount of steam over the time period of the pressure rise, the average rate of steam upwelling may be determined; this steam rate can then be used to estimate the average vertical permeability to steam (kk_{rv}). This effective steam permeability is:

$$kk_{rv} = \frac{\mu_v}{\rho_v} \frac{\rho_a c_a (\Delta T \Delta z)_{tot}}{\rho_l g t h_v} \tag{1}$$

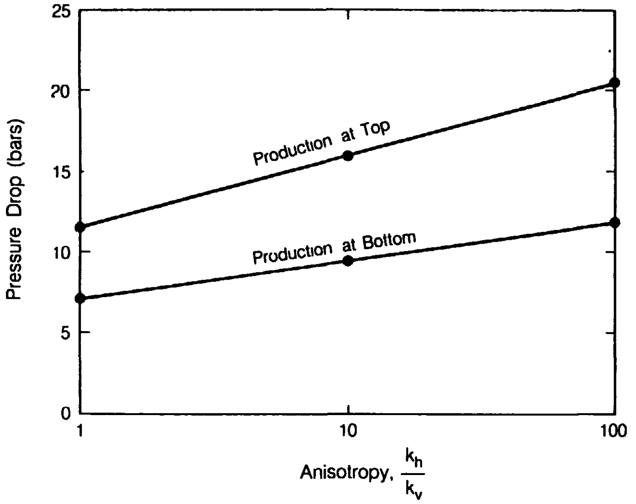

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Figure 10. Relationship between the stabilized pressure decline and permeability anisotropy for cases with deep or shallow feed zones.

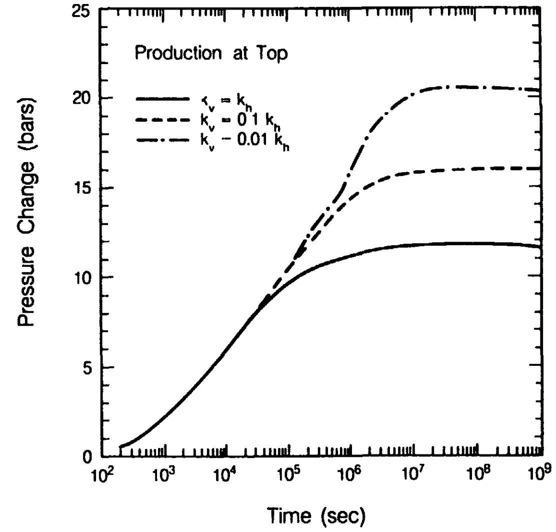

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Figure 11. Pressure decline at the well, when fluids are produced from a shallow feed zone. Different vertical permeabilities are used.

Where μ_v and ρ_v are the viscosity and density of vapor, respectively, $\rho_a c_a$ is the total fluid rock volumetric heat capacity, ρ_l is the liquid density, g is the gravitational constant, t is time and h_v is the enthalpy of vapor. The term $(\Delta T \Delta z)_{tot}$ is the total temperature change at the top of the reservoir integrated over the vertical extend of the temperature rise. This term causes the most difficulty in obtaining estimate for kk_{rv}, and requires pressure data from several observation wells with shallow feed zones at different elevations.

PRODUCTION AT TOP OF RESERVOIR

Several cases were simulated with fluid production at the top of the reservoir (see Fig. 1). Again a constant fluid production of 15 kg/s is specified. Figure 11 shows the pressure transients at the production interval for cases with different vertical permeability (anisotropy). Comparison of the results shown in Figure 11 with those of Figure 2 indicates that for the same production rate the pressure decline is considerably higher for the shallow production case. This is caused by gravity effects, which enhance recharge to a well with a deep feed zone, but oppose upward recharge of liquid water in the case of shallow production. However, the large pressure decline during shallow production overcomes the gravity effects and evokes significant upward recharge of liquid water. This liquid recharge reduces the enthalpy of the produced fluids as shown in Figure 12, and the pressure decline stabilizes.

As was observed for the case of deep production, the pressure decline for the various vertical permeabilities is also approximately a linear function of the logarithm of the anisotropy for the shallow production case (Fig. 11). Figure 13 shows the pressure transients for various observation points in the shallow production layer for the case with isotropic permeability. As expected the pressures stabilize at late times in the observation wells due to the recharge from depth. We attempted to fit these data to type curves based upon a partial penetration model using the appropriate geometrical constants ($r/H = 0.33$, $L/H = 0.2$, $z/H = 0.10$). As shown in Figure 14 the type curve does not match the entire data set very well, as the simulated data show more pressure stabilization than do the type curves. The pressure stabilization is due primarily to upflow of steam and condensation in the shallow production layer. The match with the early time data gives reasonable estimates of the transmissivity of the shallow production layer; the match with the later time data yields transmissivity values that are too high. Figure 15 shows the pressure transients for various observation points

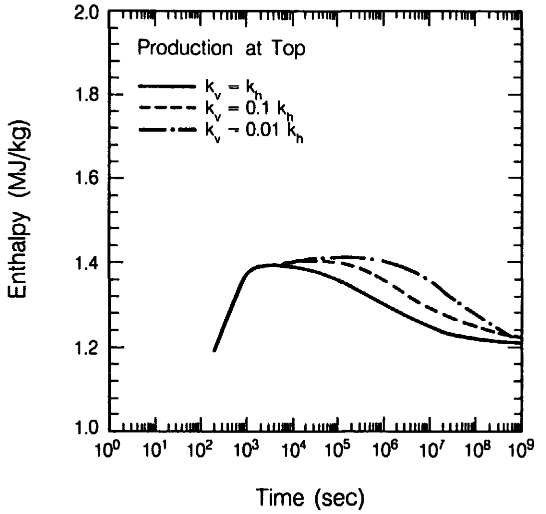

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Figure 12. Flowing enthalpy of the produced fluids for shallow production and various values of the vertical permeability.

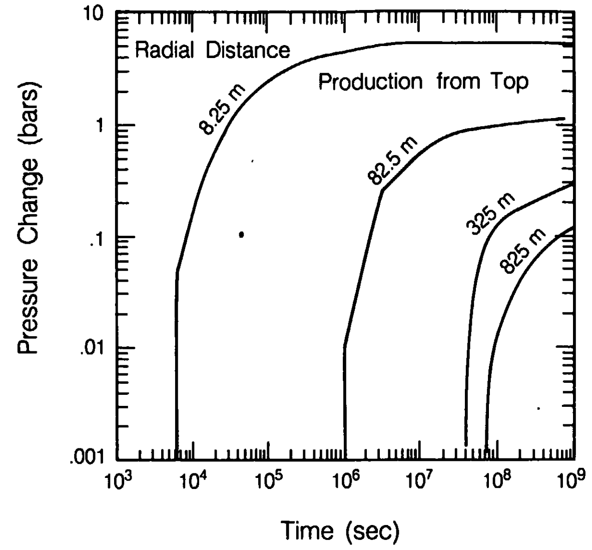

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Figure 13. Pressure transients for shallow observation points located at different radial distances from the well. Fluids are produced from a shallow feed zone.

at the bottom of the system. These data are again generated for the isotropic reservoir case, and as shown in the figure, the data can be matched reasonably well using the Theis type curve. Surprisingly, the resulting transmissivity values agree reasonably well with the overall transmissivity of the system (2.5×10^{-11} m^3). For the cases with anisotropy the pressure transients are much more complex and can not be analyzed using any of the available type curves.

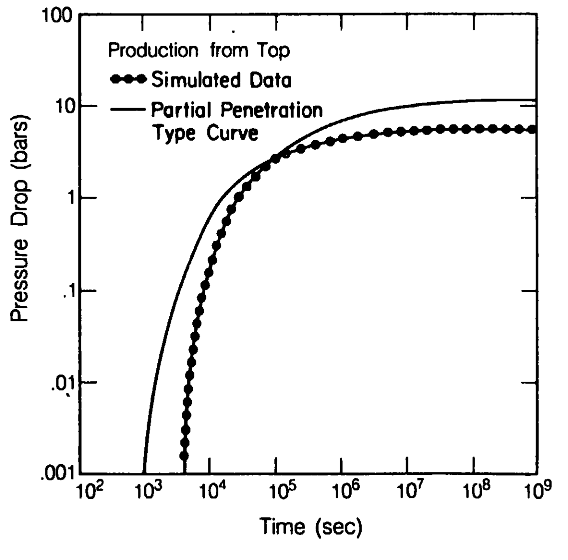

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Figure 14. Partial penetration type curves compared to simulated pressure transients at a radial distance of 83 m from the well. Fluids are produced from a shallow feed zone.

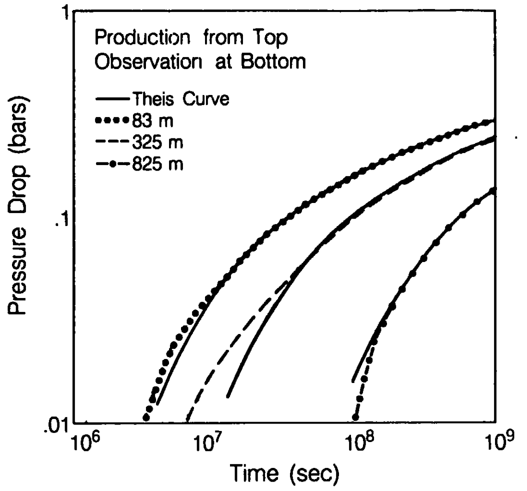

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Figure 15. Simulated pressure transients at deep observation points located at different radial distances from the well. The simulated pressure transients are matched by the Theis curve.

CONCLUSIONS

Numerical simulation methods are used to investigate gravity effects on pressure transient data and depletion patterns in two-phase reservoirs. The studies show that both gravity and production from localized feed zones can have significant effects upon the pressure transient data. The following general conclusions can be made:

(1) Production from a deep feed zone gives rise to an efficient gravity drainage mechanism that causes only gradual long-term pressure changes at the well.

(2) If the vertical permeability is significant, (more than four orders of magnitude less than the horizontal permeability for the cases studied), reservoir depletion primarily takes place at the top of the reservoir, with the development of an expanding steam-dominated zone.

(3) The pressures in the steam-dominated zone remain relatively constant during the production period simulated, resulting in a leveling of the pressure decline at observation points (wells). However, at early times pressures may actually increase at shallow depth due to upflow of steam and condensation.

(4) Production from deep feed zones evokes recharge of cooler fluids from shallow regions, and a subcooled liquid-dominated zone develops in the middle of the reservoir system.

(5) Production from shallow feeds results in considerably higher pressure drops than those from deeper zones, because of gravity effects.

(6) Upward flow of liquid reduces enthalpies in the produced fluids, and stabilizes pressures more than would be expected based upon the partial penetration theory.

(7) The studies presented here only consider a few possible cases using a simplified model. Much more work is

needed before pressure transients from two-phase reservoirs with localized feed zones can reliably be interpreted.

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REFERENCES

Cox, B. L. and Bodvarsson, G. S., 1985. Preliminary studies of two-phase effects on pressure transient data, Proc. Geothermal Reservoir Engineering Workshop, Vol. 11, Stanford University, in press.

Earlougher, Jr., R. C., 1977. Advances in Well Test Analysis, Society of Petroleum Engineers, Monograph 5.

Garg, S. K., 1978. Pressure transient analysis for two-phase (liquid water/steam) geothermal reservoirs, *Soc. Petr. Eng. Journal,* Vol. 20, No. 6, pp. 206-214.

Grant, M. A., 1978. Two-phase linear geothermal pressure transients: A comparison with single-phase transients, *New Zealand Journal of Science,* Vol. 21, pp. 355-364.

Grant, M. A., 1980. The testing of KA28-pressure analysis in a two-phase reservoir, Proc. Geothermal Reservoir Engineering Workshop, Vol. 6, Stanford University, pp. 170-177.

Hantush, M. S., 1960. Modification of the theory of leaky aquifers, *Journal Geophysical Research,* Vol. 56, p. 3713.

Martin, J. C., Wegner, R. E. and Kelsey, F. J., 1976. One dimensional convective and conductive geothermal heat flow, Proc. Geothermal Reservoir Engineering Workshop, Vol. 2, Stanford University, pp. 251-261.

Moench, A., 1978. The effects of thermal conduction upon pressure drawdown and buildup in fissured vapor-dominated geothermal reservoirs, Proc. Geothermal Reservoir Engineering Workshop, Vol. 4, Stanford University, pp. 112-117.

Moench A. F. and Atkinson, P. G., 1978. Transient pressure analysis in geothermal steam reservoirs with an immobile vaporising liquid phase, *Geothermics,* Vol. 7, pp. 253-264.

O'Sullivan, M. J., 1981. A similarity method for geothermal well test analysis, *Water Resources Research,* Vol. 17, No. 2, pp. 390-398.

Pruess, K., 1982. Development of the general purpose simulator MULKOM, 1982 Annual Report, Earth Sciences Division, Lawrence Berkeley Laboratory, Berkeley, CA, p. 133-134.

Witherspoon, P. A., Javandel, I., Neuman, S. P. and Freeze, R. A., 1967. Interpretation of Aquifer Gas Storage Conditions from Water Pumping Tests, American Gas Association Monograph, New York, 273 pp.