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THE EFFECT OF THERMAL CONDUCTION UPON PRESSURE

DRAWDOWN AND BUILDUP IN FISSURED,

VAPOR-DOMINATED GEOTHERMAL RESERVOIRS

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Introduction

An analysis of steam-pressure behavior in a vapor-dominated geothermal reservoir with an immobile vaporizing liquid phase was presented by Moench and Atkinson (1977) at the Third Stanford Workshop on Geothermal Reservoir Engineering, and later expanded by Moench and Atkinson (1978). In that study a finite-difference model was used to demonstrate the effects of phase change in the reservoir upon pressure drawdown and buildup. In this paper that model is modified to incorporate heat transfer from blocks of impermeable rock to thin, highly-permeable, porous fissures. The purpose of this study is to demonstrate the added effect of heat transfer of this type upon the transient pressure response of a vapor-dominated geothermal reservoir.

Hypothetical Model

In the present study the vapor-dominated reservoir is assumed to be composed of a random assortment of highly permeable, porous fissures separated by blocks of impermeable rock, as illustrated in figure 1a. The fissures and blocks are initially at the same constant temperature throughout. With the onset of well discharge, pressure reductions induce vaporization of liquid water within the fissures. The resulting temperature decline induces transfer of heat by conduction from the adjacent blocks.

In order to make the problem mathematically tractable, the conceptual model is idealized as shown in figure 1b. Alternating layers of fissures and blocks of constant thickness are assumed to extend in the radial direction to infinity. The thickness of the impermeable block is assumed to represent the average thickness of the blocks in the actual reservoir. The fissures are assumed to be filled initially with a uniform distribution of liquid water and steam at a fixed saturated-vapor pressure. The initial water content of the fissure is sufficiently low that changes in saturation do not appreciably change the permeability to steam. Well discharge and fissure permeability, porosity, and thermal properties are assumed constant to simplify interpretation of the results.

DISCLAIMER

It is also assumed, as in the model of Moench and Atkinson (1978), that steam and liquid water in the fissure are in local thermal equilibrium with the solid material in the fissure and that effects of vapor-pressure lowering are negligible. Effects of the latter type were considered by Moench and Herkelrath (1978).

Approach

Theoretical equations for the flow of steam through porous reservoirs in the presence of immobile vaporizing or condensing liquid water are given by Moench and Atkinson (1978). In that study it was assumed that the only temperature changes to occur in the reservoir are those due to vaporization or condensation. In this analysis temperature changes are also assumed to occur in response to heat conduction from impermeable rocks bounding permeable fissures. Moreover, in the approach that follows it is assumed that the temperature distribution across the fissure is constant and that smoothly varying temperature changes can be approximated by step changes.

The finite-difference model of Moench and Atkinson (1978) computes temperature changes at each node. These time-varying temperature changes are used to compute the flux of conductive heat normal to the fissure, at the boundary between fissure and block. A convolution equation for this calculation was derived using an analytical expression for temperature response in a slab of finite thickness, insulated at one end, and subject to an instantaneous change in temperature at the other (Carslaw and Jaeger, 1959, p. 97).

Calculated heat conduction to or from the fissure is averaged over the width of the fissure and put into the energy equation as a source term for calculation of the necessary temperature changes. Values of the thermal conductivity and diffusivity used in the analysis are given in table 2. Computation of the distributions of pressure, temperature, and saturation is carried out in the manner described by Moench and Atkinson (1978).

Results

Figure 2 shows computed dimensionless pressure drawdown (P_D vs. log t_D) in the producing well with and without effects of thermal conduction. As shown previously by Moench and Atkinson (1977), pressure drawdown is delayed in time over that expected for a noncondensable gas. This delay depends upon the initial liquid-water saturation and upon the heat capacity of the reservoir rock. In figure 2 the exponential integral solution for noncondensable gas is shown for comparison to illustrate the delay. Parameters used are listed in table 1. Heat conduction is computed for a block of infinite thickness. The addition of heat to the producing fissures can be seen to cause only a slight decrease in the rate of pressure decline at large times.

Figure 3 shows computed dimensionless pressure buildup in the production well as influenced by heat conduction from a block of infinite thickness. As explained by Moench and Atkinson (1977), pressure buildup exhibits an anomalous plateau caused by condensation in the reservoir near the well. In the examples shown by Moench and Atkinson (1977), obtained without the influence of heat conduction, the shape of the recovery curve is independent of production time for a radially ininfinite system. An example is shown in figure 3 for comparison. Figure 3 shows that the greater the production time the higher the computed pressure plateau when heat conduction is included.

Figures 4 and 5 illustrate the effect of heat conduction from blocks of finite thickness upon computed pressure buildup. Figure 4 shows that increased production time causes no further shift in the computed pressure buildup. Figure 5 shows the effect of various block thicknesses upon pressure buildup after a large production time. Thicker blocks are able to supply more heat and hence able to shift the pressure plateau to a higher level than thinner blocks.

Liquid-water saturation in the fissure near the wellbore increases to the value it had prior to production if pressure buildup is allowed to continue indefinitely. Figure 6 shows the effect of thermal conducting layers of different thickness upon the rate of saturation recovery. The rate of recovery in the case of no conduction is shown for comparison. The thicker the impermeable block, the longer it takes for the liquid saturation to recover fully.

The liquid-saturation distribution at different times during production is shown in figure 7 under conditions with and without conduction. At early times the effect of conduction is negligible but with the passage of time the shape of the saturation distribution curve changes as thermal conduction becomes significant. Conduction of heat into the fissure tends to steepen the saturation distribution.

Conclusions

It has been shown that the conduction of heat into highly permeable fissures from blocks of impermeable rocks might have a significant effect upon the pressure transient behavior of wells in vapor-dominated geothermal reservoirs. The effect upon drawdown is to bring about a slight decrease in the rate of pressure decline. The effect upon pressure recovery is more profound as the heat input brings about a significant shift in the location of the condensation plateau. Conduction of heat also steepens the saturation profile in the flashing zone and decreases the rate of condensation in the vicinity of the wellbore.

References

Carslaw, H. S., and Jaeger, J. C., 1959, Conduction of Heat in Solids: Oxford at the Clarendon Press, London.

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Moench, A. F., and Atkinson, P. G., 1978, Transient-pressure analysis in geothermal steam reservoirs with an immobile vaporizing liquid phase: Geothermics (in press).

Moench, A. F., and Herkelrath, W. N., 1978, The effect of vapor-pressure lowering upon pressure drawdown and buildup in geothermal steam wells: Transactions, Geothermal Resources Council Annual Meeting, Hilo, Hawaii, July 25-27, p. 465-468.

Table 1. Notation

P_D	(dimensionless pressure) $= \frac{\pi k h M_W}{q \mu Z_i RT}(P_i^2 - P^2)$	t_D	(dimensionless time) $= \frac{k P_i t}{\phi \mu r_w^2}$
r_D	(dimensionless distance) $= r/r_w$	K	thermal conductivity of impermeable block
		α	thermal diffusivity of impermeable block
r	radial distance	ℓ	thickness of impermeable block
r_w	well radius	S	liquid-water saturation (percent of void space)
q	production rate	S_i	initial liquid-water saturation
P	pressure		
P_i	initial pressure	t_0	production time
k	permeability	Δt	time since shut in
h	fissure thickness	Z_i	initial compressibility factor
t	time	M_w	molecular weight of water
R	gas constant	ϕ	porosity
T	temperature		
μ	steam viscosity		

Table 2. Values of Parameters Used

P_i	30×10^6 dynes/cm^2	ϕ	0.10
k	10×10^{-8} cm^2	T	507 K
K	1.67×10^5 dyne/(°C s)	S_i	0.10
α	8.4×10^{-3} cm^2/s	ρ_s	2.3 g/cm^3
h	100 cm	$c_{\rho s}$	9.6×10^6 dyne-cm/(g°C)
q	6.94×10^3 g/s	r_w	100 cm

NOTE: Remaining parameters are known properties of water at prevailing temperature and pressure

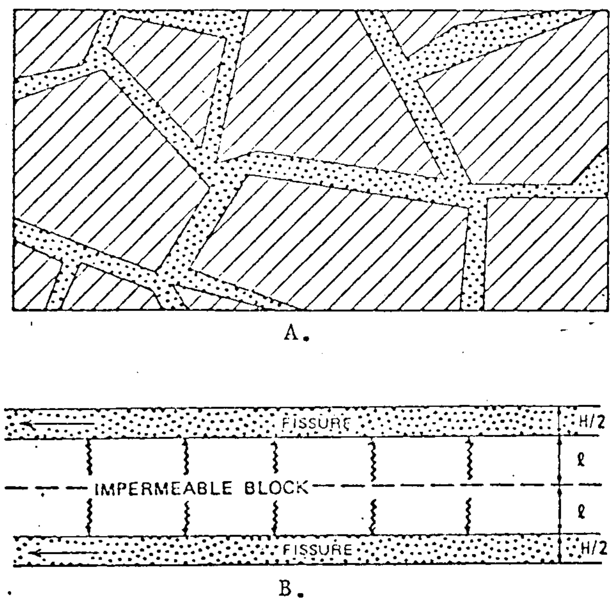

Figure 1. Vapor-dominated geothermal reservoirs

A. Hypothetical fractured reservoir composed of porous fissures and impermeable blocks

B. Idealized block and fissure reservoir used in the model

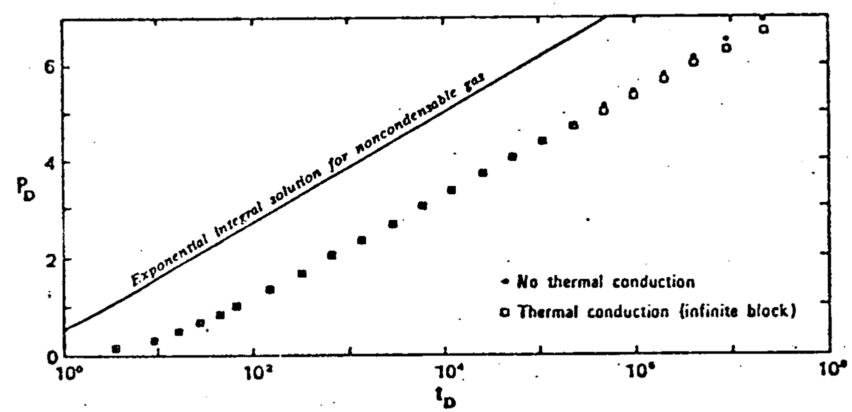

Figure 2. Pressure drawdown in producing well with and without thermal conduction

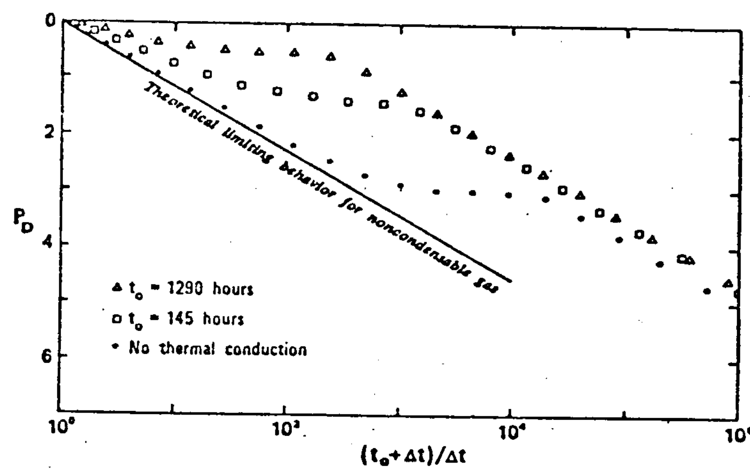

Figure 3. Pressure buildup after different production times — fissure bounded by conducting layers of infinite thickness

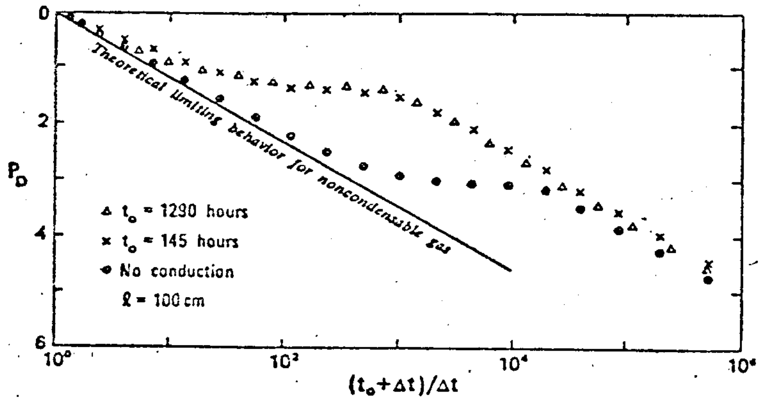

Figure 4. Pressure buildup after different production times — fissure bounded by conducting layers of finite thickness

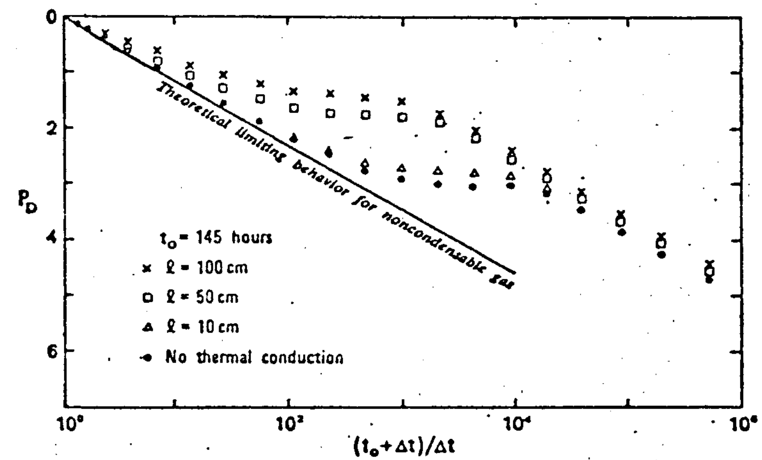

Figure 5. Pressure buildup after a fixed production time — fissure bounded by conducting layers of different thicknesses

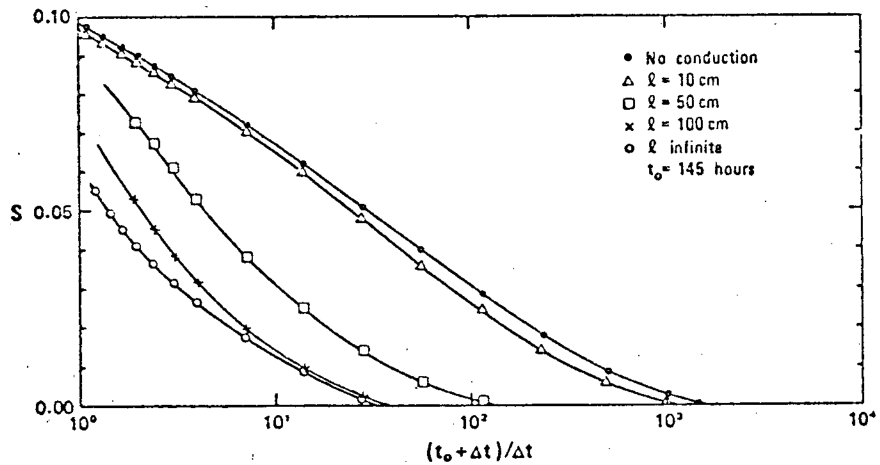

Figure 6. Saturation buildup near well bottom — fissure bounded by conducting layers of different thicknesses

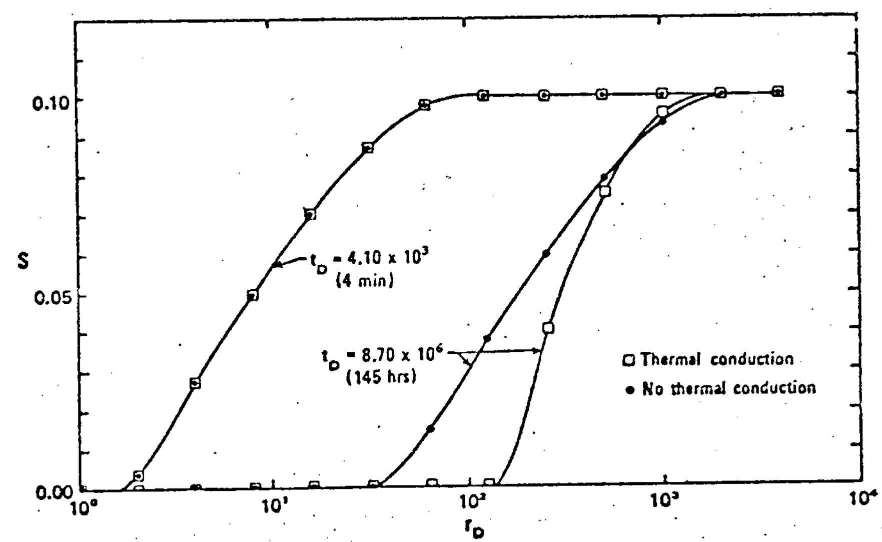

Figure 7. Radial saturation distribution at different times with and without thermal conduction