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ONE-DIMENSIONAL STEAM FLOW IN POROUS MEDIA UNDER DESORPTION

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ABSTRACT

Performance forecasting for an hypothetical field with Geysers greywacke rock is performed to demonstrate the importance of desorption effect. The actual adsorption isotherm was found to be well approximated by the Langmuir equation. Results obtained suggest that adsorption is the dominant mechanism for steam in geothermal reservoirs.

OBJECTIVE

Adsorption was investigated in connection with the vapor-pressure lowering phenomena in geothermal reservoirs (Hsieh and Ramey, 1983). Results obtained show that adsorption is a plausible mechanism for steam storage in the reservoir and does provide an explanation for the vapor-pressure lowering phenomena. Recent studies of adsorption in geothermal reservoirs focus on estimates of resource size and reservoir longevity (Economides and Miller, 1985; Ramey, 1990).

The purpose of this work is to incorporate the desorption model in the equation for steam flow in geothermal reservoirs for reservoir performance forecasting. We simulate vertical flow in the reservoir in one-dimension, assuming the steam to be superheated and desorption to be the mechanism for steam generation in reservoir for the case of production.

MATHEMATICAL MODEL

The steam flow model used is similar to the one presented by Herkelrath and Moench (1982) and Herkelrath and others (1983). The porous medium is assumed to be homogeneous and isotropic and the adsorbed water is assumed to be immobile. A mass balance for the flow of steam is:

$$\frac{\partial \phi \rho_v (1 - S_w)}{\partial t} + \phi \rho_w \frac{\partial S_w}{\partial t} - \frac{\partial}{\partial z} [\frac{k}{\mu} \rho_v (\frac{dp}{dz} - \rho_v g)] + q = 0 \quad (1)$$

The second term in Equation 1 describes the mass transfer between the adsorbed water and steam. It is a sink term during adsorption and a source term when desorption occurs. The fourth term represents the production of steam through wells.

We neglect an energy balance, assuming that the changes in temperature in the reservoir (primary due to vaporization of adsorbed liquid, (Herkelrath, Moench and O'Neal (1983)) are small.

Adsorption is described phenomenologically in terms of an empirical adsorption function, $X = f(p,T)$ where X is the amount adsorbed, customarily expressed as gram water/gram rock. One usually measures the adsorption isotherm, $X = f\tau(p)$. In this work, the adsorption isotherm is assumed to be invariant with temperature (Hsieh and Ramey, 1983; Herkelrath, Moench and O'Neal, 1983). We assume also that there is no hysteresis between adsorption and desorption. Bumb and McKee (1988) observed that the Langmuir (1909) isotherm represents methane adsorption on coal very well. Although the Langmuir expression has largely been replaced by the BET equation (Hsieh and Ramey, 1983), the Langmuir equation was tested against water vapor adsorption data for Topopah Spring welded tuff (Herkelrath, Moench and O'Neal, 1985); unpublished Geysers greywacke water vapor adsorption data; Herkel-

rath, 1990). Surprisingly, the equation was found to match measured adsorption data over the *entire* relative pressure range to $p/p_0 = 1$. The Langmuir equation has the form

$$X = \frac{p/p_0}{a + b(p/p_0)} \qquad (2)$$

with p_0 as saturation pressure.

This equation was found to match the unpublished greywacke water vapor adsorption data and other water vapor data. Figure 1 presents a comparison of Equation 2 and experimental measurements. The agreement is reasonable, and surprising. The BET equation did *not* match the data over the entire pressure range.

PROCEDURE

Steam is treated as a real gas and the psuedo-pressure substitution is applied to Equation 1. Equation 1 is rewritten in terms of X, and then in terms of a psuedo-pressure $m(p)$ (Al-Hussainy, Ramey and Crawford, 1966):

where p_m is an arbitrary pressure, perhaps at the lowest pressure of interest in the problem.

$$m(p) = \int_{p_m}^{p} \frac{p}{\mu(p)z(P)} dp \qquad (3)$$

The resulting equation has a form similar to the diffusivity equation:

$$A\frac{\partial m}{\partial t} + B\frac{\partial^2 m}{\partial x^2} + C\frac{\partial m}{\partial x} + qRT = 0 \qquad (4)$$

where:

$$A = \phi M \mu C_g (1 - \frac{\rho_r}{\rho_w}\frac{1-\phi}{\phi}X) + (\frac{zRT}{p_v} - \frac{M}{\rho_w})\rho_r(1-\phi)\mu\frac{\partial X}{\partial p_v}$$

$$B = -MK$$

$$C = \frac{M^2}{RT}\frac{2KgP_vC_g}{z}$$

where C_g is the isothermal compressibility of steam, p_r the rock density, and z is the gas law deviation factor.

Equation 5 is solved by finite-difference methods. The solution in terms of $m(p)$ may be transformed to pressure p using a chart of $m(p)$ vs. p.

RESULTS

The computer program developed was first checked for the flow of air in porous media (no adsorption) by comparing results with those of Aronofsky and Jenkins (1951). Results are not shown. However, very good agreement was obtained.

The program was then checked for the case of steam adsorption in natural soil considered by Herkelrath and
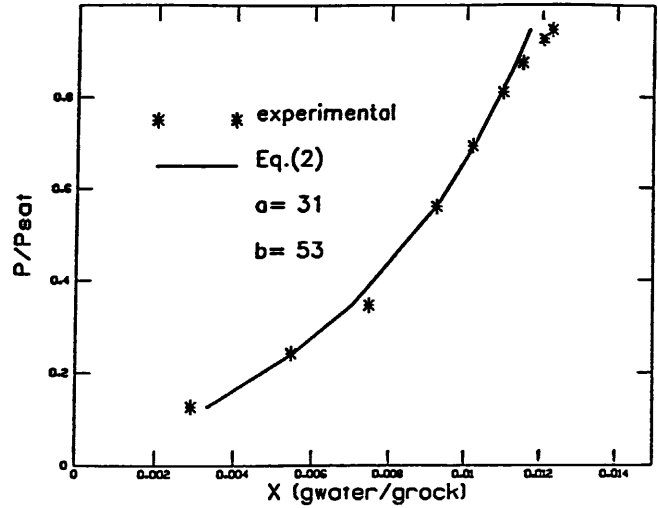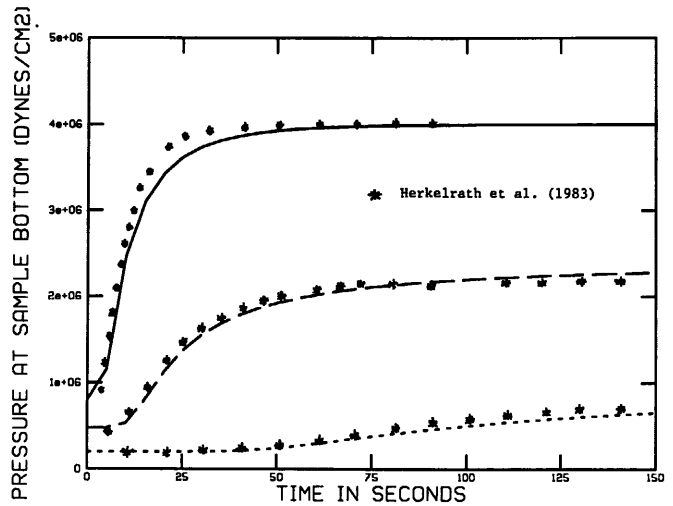

Figure 1. Adsorption isotherm.

Figure 2. Pressure response at the closed end of a core subjected to an abrupt increase in pressure at the other end.

others (1983). Acceptable agreement was obtained (Figure 2).

The model investigated considers steam extraction under either constant pressure or under constant discharge rate. Regarding the last case, we may switch the constant rate discharge mode to constant pressure mode when the pressure in the producing block becomes lower than a specificed pressure. Steam is assumed to be initially saturated. It is superheated and coexists in equilibrium with adsorbed water in the reservoir during the desorption process. Although the transient steam injection program was initially prepared to model transient benchscale experiments like those described by Herkelrath, Moench and O'Neal (1983), the program may be used to study behavior of full-scale geothermal systems like a Geysers field unit. The example considered is a 50 MW unit

which requires a steam rate of 1 MMlb/hr steam. The reservoir is a column of greywacke rock 5,000 feet high, having an area of 400 acres, 0.1 porsity and a vertical permeability of 300 md. Initial conditions were saturated steam at 500°F. The desorption process, associated with the decrease of p/p_o, is assumed to be described by Equation 2.

We are interested in a reservoir engineering study of vapor-dominated systems. A graph of p/z vs cumulative production and production rate vs time are used for analysis. Although plots of p/z vs cumulative production do not give straight lines to estimate initial steam in place (Ramey, 1990), some useful information still can be collected.
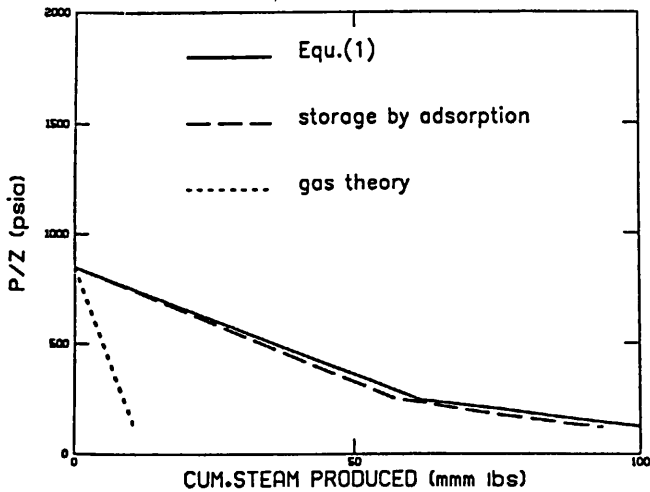

Figure 3. Production under constant pressure.

To investigate the adsorption effect and the compression effect in the geothermal reservoir, we solve Equation 1 for cases without the adsorption term (gas theory) and without the compression term (steam can only be stored as adsorbed water). Figures 3, 4 and 5 present results obtained for the case of production under constant pressure and for the case with specified rate and then constant pressure. The specified maximum rate is taken to be 10^6 lb/hr, and the lowest pressure in the producing bloc to be 114.7 psia.

Figure 3 shows the pressure behavior in the reservoir under production at a specified pressure. The strong similarity between the p/z behavior for the case of compression and adsorption and for the case of adsorption alone suggests that the steam stored in pore space is negligible. Furthermore, the shapes of those p/z vs cumulative production curves show some resemblance to the shape of the desorption isotherm in Figure 1. This may be attributed to the equilibrium state of the reservoir under production,
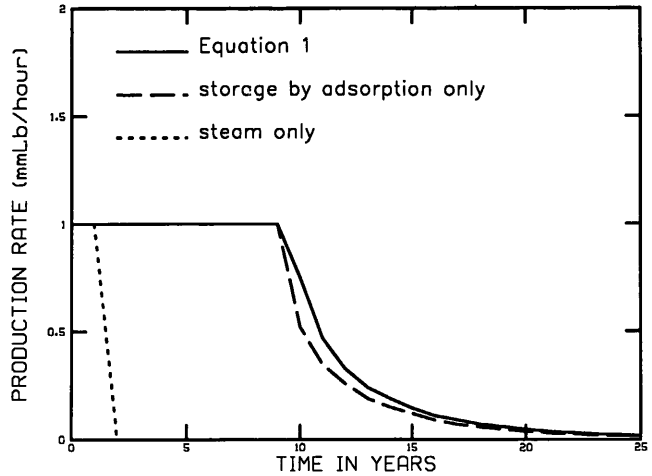

Figure 4. Production history according to different theories.

most of the steam vaporized when desorption are produced. For comparison, the straight line shape, according to gas theory, assuming steam released by free expansion is shown in the same figure.

Figure 4 presents production history for the case of specified rate. It confirms that steam is solely stored by adsorption and demonstrates the effect of adsorption on production forecasting.

Finally, the p/z behavior obtained for the last case does show a shape similar to the one observed for the Big Geyser area shallow zone and for the Italian reservoirs (Ramey, 1980). This is presented in Figure 5. It looks significantly different from those in Figure 3. This may be attributed to the fact that the desorption process has been monitored when a flow rate is specified.
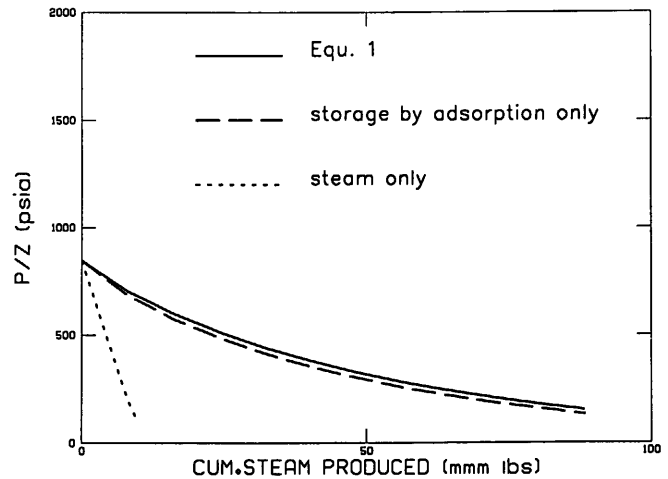

Figure 5. P/Z behavior according to different theories.

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