PROCEEDINGS, Sixteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 23-25, 1991
SGP-TR-134

One-Dimensional Steam Flow in Porous Media under Desorption

Cuong Phu Nghiem and Henry J. Ramey Jr.

Stanford University

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 reservoir (Hsieh and Ramey, 1980). Results obtained show that adsorption is a plausible mechanism for steam storage in 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 and 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 the vertical flow in reservoir in one- dimension, assuming the steam to be superheated and desorption as 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 et al. (1982,1983). 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:

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

The second term in Eq.1 describes the mass tranfer 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 et al. (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, $X = f_T(p)$. In this work, the adsorption isotherm is assumed to be invariant with temperature (Hseih and Ramey, 1980/Herkelrath et al. 1983). We assume also that there is no hysteresis between adsorption and desorption. Bumb and Mc Kee (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 and O'Neal II (1985); and unpublished Geysers greywacke water vapor adsorption data, Herkelrath (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

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

with p_0 as saturation pressure.

This equation was found to match the unpublished greywacke water vapor adsorption data and other water vapor data. Fig.1 presents a comparison of Eq.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 pseudo-pressure substitution is applied to Eq.1. Eq.1 is rewritten in terms of X, and then in terms of a pseudo-pressure m(p), see Al-Hussainy, et al., 1966:

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

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

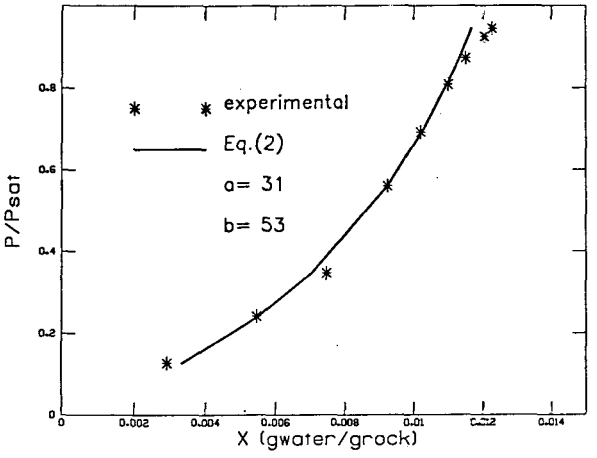

Fig. 1. Adsorption isotherm

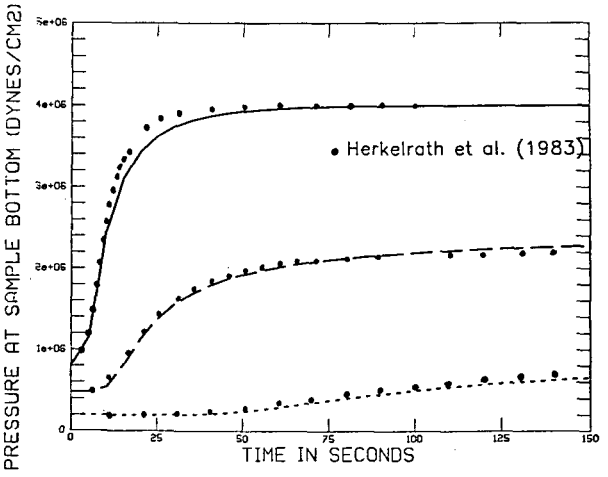

Fig. 2. Pressure response at the closed end of a core subjected to an abrupt increase increase in pressure at the other end

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, ρ_r the rock density, and z is the gas law deviation factor.

Eq.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, et al., (1983). Acceptable agreement was obtained, Fig.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 specified 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 bench-scale experiments like those described by Herkelrath, et al., (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 5000 feet high, having an area of 400 acres, 0.1 porosity and a vertical permeability of 300 md. Initial conditions were saturated steam at 500^oF. The desorption process, associated with the decrease of p/p_o, is assumed to be described by Eq.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.

To investigate the adsorption effect and the compression effect in the geothermal reservoir, we solve Eq.1, for cases without the adsorption term (gas theory) and without the compression term (steam can only be stored as adsorbed water). Figs.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 lbs/hour, and the lowest pressure in the producing bloc to be 114.7 psia.

Fig.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

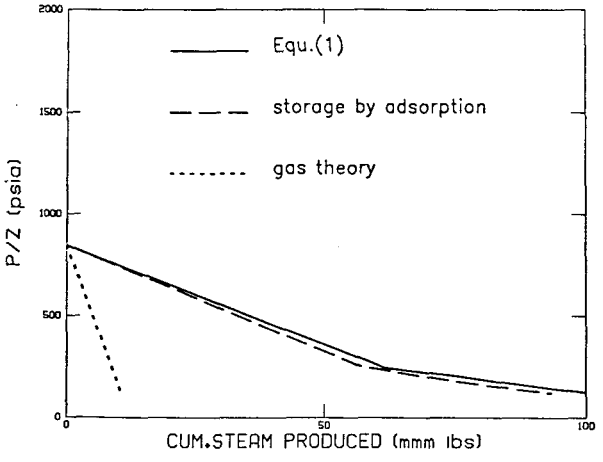

Fig. 3. Production under constant pressure

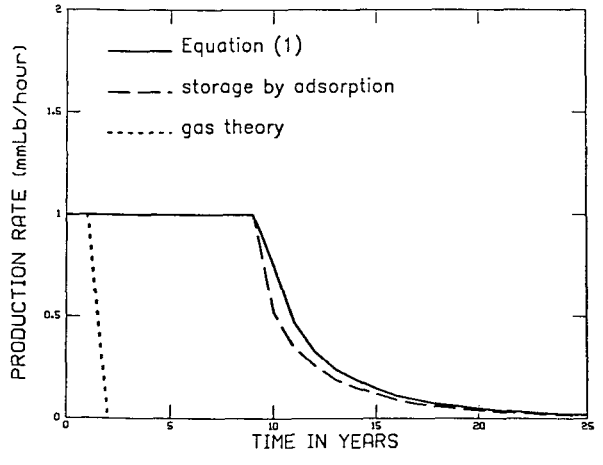

Fig. 4. Production history according to different theories

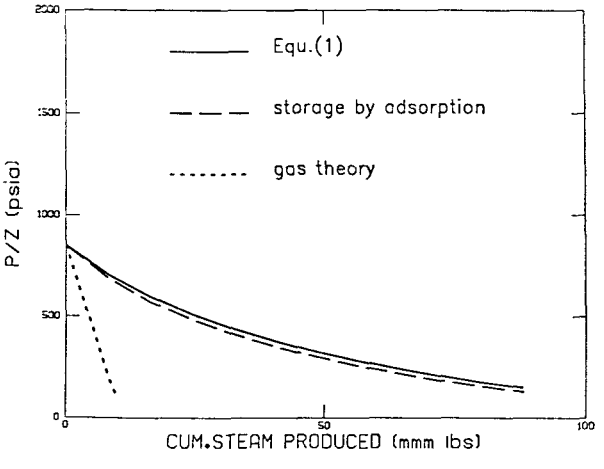

Fig. 5. P/Z behavior according to different theories

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 Fig.1. This may be attributed to the equilibrium state of the reservoir under production, 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.

Fig.4 presents production history for the case of specified rate. It confirms that steam is solely stored by adsorption and demonstrates the 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 found observed for the Big Geyser Area Shallow Zone and for the italian reservoirs (Ramey, 1980) is presented in Fig.5. It looks significantly different from those in Fig.3. This may be attributed to the fact that the desorption process has been monitored when a flow rate is specified.

REFERENCES

Al-Hussainy, R., Ramey Jr., H.J. and Crawford, P.B.: *The Flow of Real Gases Through Porous Media*, JPT (May 1966), 624-636.

Aronofsky, J.S., and Jenkins, R.: *Unsteady Flow Of Gas Through Porous Media, One-Dimensional Case*, Proc. First U.S Ntl Cong. Appl. Mech., Am. Soc. Mech. Engrs. (June, 1951).

Bumb, A.C. and McKee, C.R.: *Gas-Well Testing in the Presence of Desorption for Coalbed Methane and Devonian Shale.* SPEFE (March 1988), 179-185.

Economides, M.J, and Miller, F.G.: *The Effects of Adsorption Phenomena in the Evaluation of Vapour-dominated Geothermal Reservoirs.* Geothermics (1985), 14, No.1, 3-27.

Herkelrath, W.N., and Moench, A.F.: *Laboratory Investigations of the Physics of Steam Flow in a Porous Medium.* USGS Open-File Report 82-95, 1982.

Herkelrath, W.N., Moench, A.F., and C.F.O'Neal II: *Laboratory Investigations of Steam Flow in Porous Medium. Water Resources Research* (August 1983), 19, No.4, 931-937.

Herkelrath, W.N., and O'Neal II, C.F.: *Water Vapor Adsorption in Low Permeability Rocks.* Proc. 17th Int. Cong. Int. Assn. of Hydrogeologists (January 1985).

Herkelrath, W.N.: personal communication with H.J. Ramey Jr. (1990).

Hsieh, C.H.: *Vapor Pressure Lowering in Porous Media.* PhD Diss., Stanford University (1980).

Hsieh, C.H., and Ramey Jr., H.J.: *Vapor-Pressure Lowering in Geothermal Systems.* SPEJ (February 1983) 157-167.

Ramey Jr., H.J.: *Adsorption in Vapor-dominated Systems.* Proceedings of the Geothermal Program Review VIII The National Strategy-The Role of Geothermal Technology Development" (April 1990).