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Idaho Operations Office  
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Re: Grant No. DE FG07-90 ID12934

Dear Peggy:

Enclosed is the Quarterly Technical Report for the above Grant for the Quarter January - March, 1992.

If there are any questions feel free to phone me at (415) 723-4745.

Sincerely

Jean W. Cook  
Program Manager
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1 INVESTIGATION OF ADSORPTION/DESORPTION DURING REINJECTION AT THE GEYSERS

This work by research assistant John Hornbrook and Prof. Roland N. Horne is concerned with deriving the analytical solution for the one-dimensional flow of steam through porous media with adsorption. The research to be performed is based on the work carried earlier in this program by Nghiem and Ramey (1991). As in the work by Nghiem and Ramey (1991), the development started with the material balance in terms of Darcy's law:

\[
\frac{\partial \phi \rho_v (1 - S_w)}{\partial t} + \phi \rho_v \frac{\partial S_w}{\partial t} - \frac{\partial}{\partial x} \left[ \frac{k}{\mu} \left( \frac{dp}{dz} - \rho_v g \right) \right] + q = 0
\]  

(1)

The effects of adsorption are to be studied, so an expression relating the amount of liquid adsorbed and the liquid saturation was needed. The expression used is as follows:

\[
S_w = \frac{1 - \phi \rho_r X}{\phi \rho_w}
\]  

(2)

Pseudopressure is defined as follows:

\[
m(p) = \int_{p_m}^{p} \frac{p}{\mu(p)z(p)} dp
\]  

(3)

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where \( p \) is an arbitrary pressure. Equation (1) rewritten in terms of adsorption and pseudopressure becomes:

\[
\left( \frac{M}{2RT} \right) \left( \frac{\mu X}{p} \right) \left( 1 - \frac{p}{z} \frac{\partial z}{\partial p} \right) + \left( \frac{\mu X}{p} \right) \left( \frac{\partial X}{\partial p} \right) \left( \frac{\mu z}{p} \right) \frac{\partial m(p)}{\partial t} - \left( \frac{kM}{2RT} \right) \frac{\partial^2 m(p)}{\partial z^2} = 0
\]

(4)

where:

\[
\rho_w = \rho_w \phi + \rho_r (\phi - 1)
\]

(5)

\[
\rho_r = \frac{(\rho_w - \rho_r)(1 - \phi)\rho_r}{\rho_w}
\]

(6)

In the simplification of Equation (1), the source/sink term was set to zero, and the gravity term was assumed to be negligible. These assumptions simplified the derivation without loss of meaningful information.

Inspection of Equation (4) shows it to be of the form:

\[
f(p) \frac{\partial m(p)}{\partial t} - C \frac{\partial^2 m(p)}{\partial z^2} = 0
\]

(7)

Equation (7) is nonlinear in the first order derivative term but the extent of nonlinearity must be determined by numerical investigation over a range of pressures.

Analysis of the nonlinear term in Equation (7) (and, by analogy, Equation 4) indicates that \( f(p) \) is, indeed, a strong function of pressure. Thus, some means of solving the equation must be utilized that allows for analysis of the effects of the nonlinear term under a range of conditions. Perturbation analysis seems to be the best approach. The project is investigating perturbation methods as a way to attack the problem. The idea is to first solve a linearized form of Equation (4) which does not include adsorption and then to perturb the solution to solve the equation with adsorption effects included. Through this perturbation analysis process, insight will be gained into the importance of adsorption as a fluid storage and propagation mechanism.
2 DRAWDOWN AND BUILDUP PRESSURE ANALYSIS IN MULTIWELL RESERVOIRS

This is the continuing work of the reservoir interpretation project performed by research assistant Xianfa Deng and Professor Roland N. Horne.

During the current quarter, the objective of this study has been to investigate how neighboring wells affect the buildup pressure data in the test well if the neighboring wells are producing during the testing.

In a typical application, there are \( n+1 \) wells; well 0 is the observation well, well 1 is the testing well producing at constant rate \( q \) until being shut at time \( t_{pD} \), and all the other neighboring wells produce at the constant rate \( q \) all the time. If the wellbore storage effect is included, the pressure solution in Laplace space for the multiwell system can be obtained by superposing finite sources in time and space,

\[
\bar{p}_D(\tau_1 D, \tau_2 D, \ldots, \tau_n D, t_{pD}, s) = \frac{(1-e^{-t_{pD}/\tau_D})K_0(\tau_1 D \sqrt{s}) + K_0(\tau_2 D \sqrt{s}) + K_0(\tau_3 D \sqrt{s}) + \ldots + K_0(\tau_n D \sqrt{s})}{s^2(K_1(\sqrt{s}) + C_D \sqrt{s} K_0(\sqrt{s}))},
\]

or basing the abscissa on \( \frac{t_{pD}}{\tau_D} \) and using \( \frac{t_{pD}}{\tau_D} \) as the parameter,

\[
\bar{p}_D(\tau_1 D, \tau_2 D, \ldots, \tau_n D, t_{pD}, s) = \frac{r_{pD}[(1-e^{-t_{pD}/\tau_D})K_0(\tau_1 D \sqrt{s/r_{pD}}) + K_0(\tau_2 D \sqrt{s/r_{pD}}) + K_0(\tau_3 D \sqrt{s/r_{pD}}) + \ldots + K_0(\tau_n D \sqrt{s/r_{pD}})]}{s^2(K_1(\sqrt{s/r_{pD}}) + C_D \sqrt{s/r_{pD}} K_0(\sqrt{s/r_{pD}}))}
\]

where \( C_D \) is the wellbore storage coefficient, and \( r_{iD} \) is the distance between observation well 0 and well \( i \).

When \( n = 1 \), this becomes the interference case with one active well and one observation well in an infinite homogeneous reservoir. The type curves for drawdown and buildup without wellbore storage are provided by Prof. Ramey as shown in Figure 1. In this special case, the pressures at any place are the same except at the very beginning of the time if \( p_D \) is plotted vs \( \frac{t_{pD}}{\tau_D} \) with \( \frac{t_{pD}}{\tau_D} \) as the parameter( \( r_{iD} = r_{1D} = r_D \)). As can be seen from Figures 2, 3 and 4, the pressure responses depend much on the distance between
testing well and observation well if wellbore storage is considered.

Figure 5 and Figure 6 show the pressure drawdown and buildup for a six-well system, where the testing well is also the observation well. The drawdown response has contributions from all the production wells. When the testing well is shut in, the buildup response undergoes a transition until eventually following the curve corresponding to the productions of all the neighboring wells. Notice this means that the buildup pressure will eventually begin to fall again.

Figure 7 shows only the buildup part of the response for the same system. For a fixed shut-in time, $p_D$ will becomes larger than $p(t_D)$ at late time, so each curve reaches below zero at some time. The shut-in time affects the buildup pressure data very much as can be seen from Figure 7.
Figure 1: Interference pressure response vs production time

Figure 2: Pressure response vs production time and wellbore storage effect
Figure 3: Pressure response vs production time and wellbore storage effect

Figure 4: Pressure response vs production time and wellbore storage effect
Figure 5: Pressure response vs production time

Figure 6: Pressure response vs production time and wellbore storage effect
Figure 7: Pressure buildup response vs time after shut-in
3 ADSORPTION OF WATER VAPOR ON RESERVOIR ROCKS

This experimental study by postdoctoral research associate Dr. Shubo Shang and Prof. Henry J. Ramey, Jr. is continuing the experimental measurement of adsorption in reservoir rocks.

In vapor dominated geothermal systems, it has been proposed that liquid exists as adsorbed liquid in micropores (White, 1973). Evidence from both laboratory studies and field data indicates that storage of liquid as micropore fluid is probable (Ramey, 1990). Measurement of adsorption/desorption of water vapor on reservoir rocks is a crucial step in determining whether adsorption is the dominant storage mechanism for these systems.

A fully automated sorptometer by Porous Material, Inc. (PMI) is being employed in this work. Currently, a new version of the software is being installed and tested and effort is being made to choose the optimum operating conditions for steam adsorption.

The major objective of this project is to collect a large body of adsorption/desorption data from field samples. As the surface area of the rock sample is an important parameter for adsorption, measurement of surface area will be made using nitrogen adsorption. Data from Harr (1991) has revealed significant hysteresis for water adsorption/desorption on both Los Azufres (Mexico), Reykjanes (Iceland), and the Geysers Shallow Reservoir rocks. Apart from the possible chemical interaction between water and rocks at high temperature, physical heterogeneity must be responsible for different types of hysteresis measured in different water-rock systems. If possible, scanning electron micrographs (SEM) will be taken for each sample so that the structure of the rock samples can be compared to provide a better understanding of the hysteresis.

Both Hsieh and Ramey (1983) and Herkelrath et al. (1983) observed a lack of sensitivity of adsorption to temperature in some rock samples. If this can be generalized for all rock materials, considerable laboratory work can be avoided. However, this phenomena contradicts the thermodynamics of adsorption. Adsorption/desorption tests will be made at different
temperatures to be able to investigate the temperature sensitivity of the adsorption/desorption isotherms of reservoir rocks. Ultimately, we want to extrapolate the laboratory data into field conditions so that one can predict reservoir performance in correctly.

4 ADDING ADSORPTION TO A GEOTHERMAL Simulator

This work is an extension of work performed by research assistant Richard Holt together with Al Pingol of Unocal, during a summer assignment in 1991. It is being developed further in the Stanford Geothermal Program under the supervision of Prof. Ramey.

Physical adsorption of steam has increasingly become recognized as an important phenomenon in vapor dominated geothermal reservoirs. A method has been developed which allows the effects of adsorption to be modeled using TETRAD, a commercially available geothermal simulator. The method consists of replacing the standard steam table with a new steam table which has been derived to include adsorptive effects. This new steam table was generated by combining the Langmuir isotherm adsorption model with an energy and mass balance. The TETRAD simulator, when run with the pseudo steam table, approximately matches the pressure, production, and saturation behavior of a desorbing geothermal system.

Adsorption can be described as the existence of an immobile layer of liquid on the surfaces within a porous medium. The presence of an adsorbed liquid water layer in rocks has been shown experimentally to cause the vapor pressure of steam to appear to be lower than its flat surface vapor pressure for a particular temperature. The pseudo steam table accounts for this apparent vapor pressure lowering. Figure 8 shows saturated vapor pressure versus temperature for both the standard and pseudo steam tables. Notice that a geothermal system which follows the pseudo steam table will have large changes in pressure for modest changes in temperature.

A test run was made with TETRAD using the pseudo steam table and a low porosity, low permeability reservoir matrix. This test run was compared
Figure 8: Comparison of the standard and pseudo steam tables.
to an equivalent run made with Stanford Geothermal Program's adsorption simulator, ADSORB. The program ADSORB is a one-dimensional simulator which has adsorption effects built into its difference equations. The comparison of these runs shows that the pseudo steam table allows TETRAD to match the behavior of the ADSORB simulator. Injection was not investigated in this study.

A convenient method of modeling adsorption with TETRAD is to use standard steam tables while allowing for the apparent vapor pressure lowering effect of adsorption. This will require modifications of the code that describe the partial pressure of the steam phase.

The ability to include adsorption in numerical simulation has become important to operators who use simulators to make reservoir predictions. It is, however, largely impractical to write and test completely new simulator codes which have been written specifically to include adsorptive effects. If possible, it is more useful to include adsorptive effects in existing simulators. This will allow adsorption to be included only in situations or reservoirs where it is believed to occur. The objective of this study is to develop a practical means of modeling a desorbing geothermal system using the TETRAD simulator. This is accomplished through a new input card, 'DESORB'. The implementation of the DESORB card requires changes in the partial pressure calculation code in TETRAD.

The study described above was performed while Richard Holt was employed by Unocal Geothermal as a summer intern, June-September 1991. With encouragement from Prof. Ramey of SGP, the authors wrote a paper entitled, "Adding Adsorption to a Geothermal Simulator", which was presented at the Stanford Geothermal Workshop, January 1992.

A new project is presently being conceived. This new project will be both experimental and theoretical in nature. Knowledge gained from experimental studies with SGP's PMI Sorptometer will be incorporated into geothermal reservoir modeling.
5 ESTIMATION OF DESORPTION PARAMETERS FROM EXPERIMENTAL DATA

This project is being performed by research assistant Ming Qi, together with Professors Roland N. Horne and Henry J. Ramey, Jr..

A one-dimensional single porosity/permeability finite-difference simulator that includes adsorption/desorption has been developed by Cuong Phu Nghiem and Henry J. Ramey Jr. (1991). In the program, adsorption and desorption is determined by using the Langmuir equation.

The Langmuir equation has the form:

\[ X = \frac{p/p_{sat}}{A + Bp/p_{sat}} \]

Although the Langmuir equation was developed for a monolayer adsorption model, recent studies have shown that in some cases it can fit experimental data over a wide relative pressure range (Nghiem and Ramey, 1991). Thus it was suggested that the Langmuir equation could be used as an empirical equation. The two parameters (A and B) in the Langmuir equation can be determined from experimental data. During the winter quarter, a nonlinear regression program was successfully combined with the simulator to give the 'best' estimation of parameters A and B by fitting the simulated results to the transient pressure measured in Harr's experiments (Harr, 1991). Before being applied to the experimental data, the program was tested. First we generated data by running the adsorption simulator with a set of specific values of A and B, then we ran the regression program with a set of guessed parameters A0 and B0 (different from A, B). The program always succeeded in converging to the true values of A and B. Then we used this program to interpret the four transient experiments from Harr (1991). A detailed description of the experiments can be found in Harr (1991).

One experiment was run using a sample of well cuttings from well number 9.
of the Reykjanes field in Iceland. Another two experiments were run using a sample from an unknown well in the Geysers shallow reservoir but with different particle sizes. The fourth experiment was run using the sample from well OF52-11 in the Geysers shallow reservoir. The pressure calculated using the simulator was matched to the experimental pressure data measured at the closed end of the sample holder. The 'best' values of A and B were determined when the least squares match was achieved. In all four cases, the program gave relatively good matches of the pressure. Figure 9 shows one such matching plot. The parameters A and B decided from such a match can then be used in the Langmuir equation to calculate the isotherm. No experimental isotherm data were available for comparison at this time, but comparison of the calculated isotherm data and experimental isotherm data from the same samples under different experiment conditions (measured in the steady state sorptometer apparatus) indicated that they do not match each other very well.

So far only four sets of experimental data were matched. As this project continues, more experimental data will be available for further comparison. Based on this method, other forms of empirical isotherm equations will also be tested. Once a good equation is found, it will be used in matching the field data in a similar manner, using the same nonlinear regression program.

References


Figure 9: Match of Langmuir isotherm to transient experimental data.