Adding Adsorption to a Geothermal Simulator

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Abstract

Physical adsorption of steam has increasingly become recognized as an important storage mechanism 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. 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 be lower than its flat surface vapor pressure for a particular temperature[1],[2]. The pseudo steam table accounts for this vapor pressure lowering effect.

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 to an equivalent run made with Stanford Geothermal Program's 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 vapor pressure lowering effect of adsorption. This will require modifications of the equations in the code that describe the partial pressure of the steam phase.

Introduction

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.

Adsorption has been shown experimentally to cause a vapor pressure lowering effect. Conventional simulators, such as TETRAD, use a standard steam table to predict the reservoir pressure-temperature relationship. If adsorption is taking place, this standard steam table approach is inadequate. Adsorption has been shown experimentally and numerically to cause a substantial effect on the flow of steam through porous medium[1],[4],[5]. The Stanford Geothermal Program has written a one dimensional simulator program called ADSORB[5]. The ADSORB simulator has adsorptive effects built into its difference equations in a rigorous manner. Runs made with ADSORB were therefore used to represent the behavior of a system producing under desorption. Using concepts explained later, a special steam table was derived. This pseudo steam table, when placed in TETRAD's input deck, causes TETRAD to duplicate the results of the runs made with ADSORB.

The pseudo steam table, although successful in modeling adsorptive effects, is cumbersome to use.

A new pseudo steam table must be generated when any input parameters are changed. To allow convenient adsorption modeling, a new input card, DESORB, is proposed. The DESORB card will invoke a steam partial pressure lowering algorithm. The pseudo steam table run serves, however, as a test of the validity of the overall technique.

Macroscopic Effects of Adsorption

Physical adsorption of steam is caused by attractive forces between water molecules and rock surfaces. A finite layer of adsorbed liquid water forms on the rock surfaces. This layer of water has a thermodynamic behavior which is quite different from what is described by standard steam tables. The way in which the microscopic physics of adsorption affects macroscopic reservoir performance is studied here.

Ignoring capillary effects, vapor pressure is represented in steam tables as a function of temperature only. Therefore, in the absence of adsorption, the functional form of Equation 1 applies for vapor pressure.

$$(1) \qquad P_{sat}=f(T)$$

If adsorption is occurring, however, vapor pressure is a function of both temperature and liquid saturation. Thus if adsorption is occurring, the functional form of Equation 2 applies for vapor pressure.

$$(2) \qquad P_{sat}=f(T)*g(S_w)$$

The fact that adsorption causes vapor pressure to be a function of both temperature and liquid saturation is key to understanding how to model the process.

A classic model for vapor pressure lowering due to adsorption is presented by Langmuir[3]. Equation 3 is referred to as the Langmuir isotherm, and applies at a fixed temperature.

$$(3) \qquad X=\frac{(P/P_{sat})}{A + B(P/P_{sat})}$$

In Equation 3, X is mass fraction of adsorbed liquid in gram/gram rock, P is vapor pressure, Psat is steam table vapor pressure. The ratio (P/Psat) is called the steam partial pressure. The constants A and B are rock properties. In observations of experimental data, Nghiem and Ramey suggest that A=31 and B=53 may be suitable values for many reservoir rocks[5]. Equation 3 can be expressed in terms of water saturation, porosity, and densities as shown in Equation 4.

$$(4) \qquad S_w=\frac{(1-\phi)}{\phi} \frac{\rho_r}{\rho_w} X$$

The entire Langmuir isotherm behavior can be expressed using Equations 5, 6, and 7. Equations 3 and 4 are combined to produce Equation 5. Note that there is a critical water saturation, Swcrit, above which steam partial pressure is equal to 1.0. The critical water saturation is determined by Equation 7. Equations 5, 6, and 7 apply at a fixed temperature.

$$(5) \qquad (P/P_{sat})=\frac{S_w A \frac{\phi}{(1-\phi)} \frac{\rho_w}{\rho_r}}{1-S_w B \frac{\phi}{(1-\phi)} \frac{\rho_w}{\rho_r}} \qquad 0<S_w<S_{wcrit}$$

$$(6) \qquad (P/P_{sat})=1.0 \qquad S_{wcrit}<S_w<1$$

$$(7) \qquad S_{wcrit}=\frac{(1-\phi)}{\phi} \frac{\rho_r}{\rho_w} \frac{1}{(A+B)}$$

Equations 5, 6 ,and 7 are presented in graphical form in Figure 1. Note that the steam partial pressure, P/Psat, varies from 0.0 to 1.0 as water saturation varies from 0% to about 96% for this particular system.
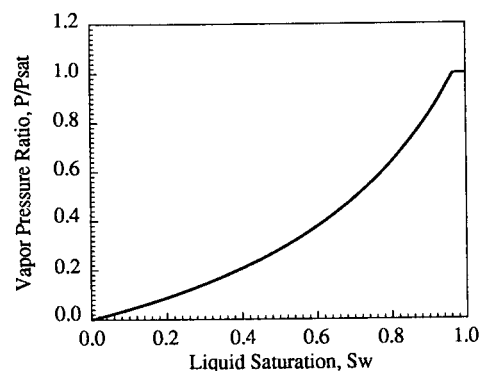

Figure 1 - The Langmuir Isotherm for A=31, B=53 and porosity= 4%. Equations 5, 6, and 7.

The ADSORB Program

A test run was made with the ADSORB program for use as a comparison to later TETRAD runs. The sample case used throughout this study is shown in Figure 2.
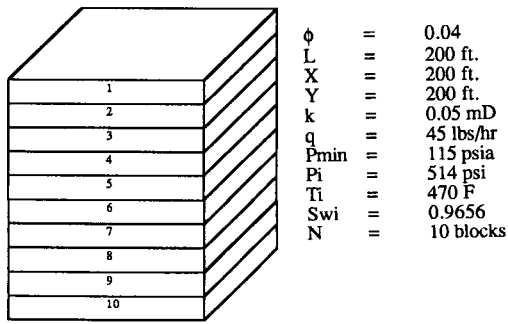
φ	=	0.04
L	=	200 ft.
X	=	200 ft.
Y	=	200 ft.
k	=	0.05 mD
q	=	45 lbs/hr
Pmin	=	115 psia
Pi	=	514 psi
Ti	=	470 F
Swi	=	0.9656
N	=	10 blocks

Figure 2 - Simulation test case for all runs in study.

A desorbing geothermal system is modeled as a porous rock with an immobile water saturation which vaporizes into the gas phase and flows to a well. Therefore, at all saturations, Krg=1.0 and Krw=0.0. Initial water saturation is set to Swcrit, which for this system is Swi=96%. A 200 foot cube of reservoir rock is used to resemble a unit of reservoir matrix located between fractures. This cube is split into 10 blocks of 20 feet each. Block #1 contains the production well. Initial production rate is set to 45 lbs steam/hour. This rate is maintained until block #1 reaches a pressure of 115 psia. At this point, block #1 produces at a constant pressure while production rate declines. The results of this ADSORB test run are shown below in Figures 3, 4, and 5.
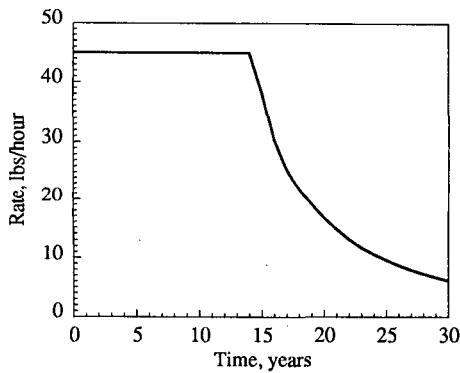

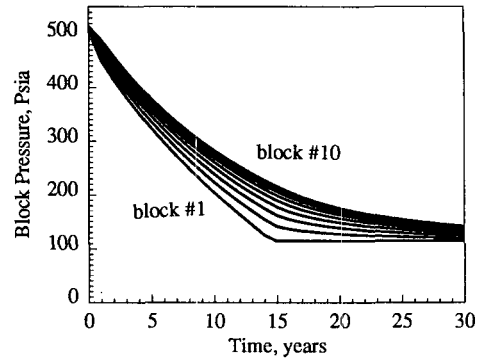**Figure 3** - Rate vs. time for ADSORB run.

Figure 4 - Pressure vs. time for each of ten blocks in ADSORB run.
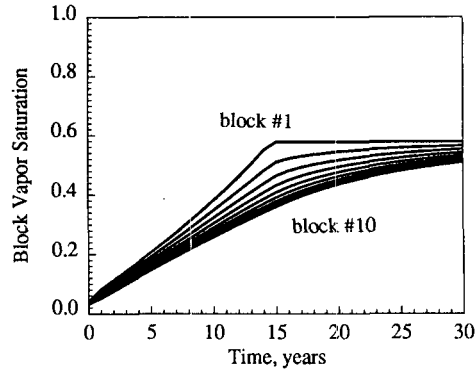

Figure 5 - Steam saturation vs. time for each of ten blocks in ADSORB run.

A Standard TETRAD Run Without Adsorption

As a starting point an initial TETRAD run was made with no provision for the inclusion of adsorption. The standard steam table was used. The input parameters and geometry exactly match those described in Figure 2. Therefore a direct comparison of the ADSORB run and this TETRAD run will show the effects that adsorption has on reservoir performance. The results of this TETRAD run are shown in Figures 6, 7, and 8.
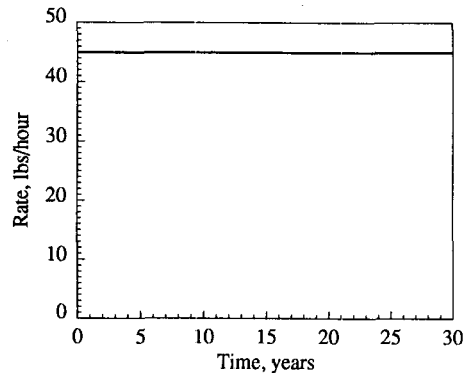

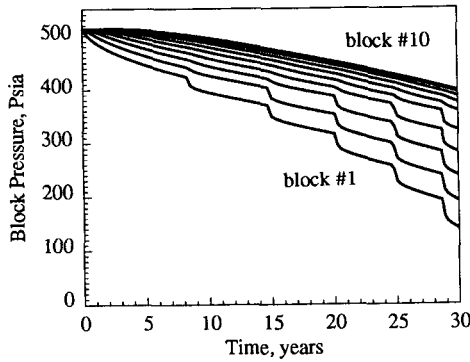**Figure 6** - Rate vs time for standard TETRAD run with no adsorption.

Figure 7 - Pressure vs. time for each of ten blocks the standard TETRAD run with no adsorption.
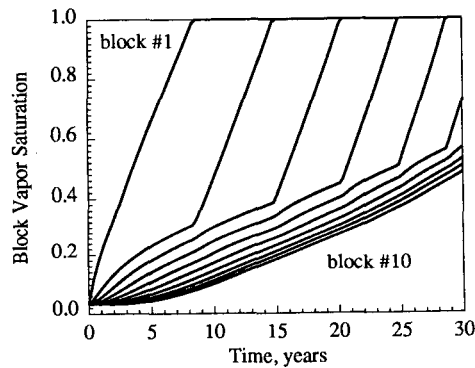

Figure 8 - Steam saturation vs. time for each of ten blocks in the standard TETRAD run with no adsorption.

In Figure 7, discontinuities in the pressure response are a numerical artifact. This is caused when a block reaches 100% gas saturation. On the comparison of the standard TETRAD run with the ADSORB run, the following observations are made:

1. The presence of adsorption reduces the length of time that the production plateau of 45 lbs/hour can be maintained. This is shown by a comparison of Figure 6 and Figure 3.

2. The presence of adsorption causes block pressures to decline more rapidly. This is shown by a comparison of Figure 7 and Figure 4.

3. The presence of adsorption prevents gas saturation from reaching 100%. This is shown by a comparison of Figure 8 and Figure 5. In the presence of adsorption, gas saturation becomes 100% only if pressure is 0 psia. Therefore, significant liquid saturations may be present at low pressures, if adsorption is taking place.

The Pseudo Steam Table

In order to incorporate adsorption into TETRAD, a technique is needed which will allow vapor pressure to be a function of both temperature and liquid saturation. In the existing version of TETRAD, steam vapor pressure is calculated by entering a standard steam table with a known block temperature and reading vapor pressure. Initial attempts to model adsorption were thus directed at the steam table.

It is desired to make the vapor pressure in the steam table such that it can approximately match the sum behavior of Equations 5, 6, and 7. A complication arises, however, because Equations 5, 6, and 7 are functions of liquid saturation, and the steam table (flat surface vapor pressure) is a function of temperature. A relationship between temperature and saturation is needed. Such a relationship will allow saturation and temperature to be used interchangeably in Equations 5, 6, and 7.

Consider a geothermal system with some finite immobile liquid saturation. As the system is produced, liquid is continuously vaporizing and flowing toward the well as steam. As this liquid vaporizes, the rock matrix cools as energy goes into vaporizing the liquid. If there is no injection, and the thermal conductivity of the system is low, then temperature can be related directly to saturation. This is done by using an energy balance.

The system of interest is a porous rock with a vaporizing immobile liquid saturation. An energy balance applied to this system produces Equation 8.

$$(8) \quad (S_{wi}-S_w) = \frac{(1-\phi)}{\phi} \frac{C_{prock}}{h_{fg}} \frac{\rho_r}{\rho_w} (T_i-T)$$

In Equation 8, two assumptions have been made. First, it is assumed that all thermal properties are independent of temperature. Second, it is assumed that the thermal capacities of the liquid water and steam saturations are negligible when compared to the rock thermal capacity. Table 1 lists the thermal properties used throughout this study.

Table 1

ϕ	=	0.04
C_{prock}	=	0.232 *btu/lbm F*
ρ_{rock}	=	2.65 *g/cc*
ρ_{H2O}	=	0.7841 *g/cc*
h_{fg}	=	770 *btu/lbm*
S_{wi}	=	0.9656
T_i	=	470 *F*

The values in Table 1 are inserted into Equation 8 and the numerical result is Equation 9.

(9) $S_w = 0.9656 - 0.024 * (470 - T)$

Equation 9 is a simple linear equation which can convert temperature values into saturation values. Using Equation 9, Sw can be substituted out of Equation 5. The result is an equation which expresses adsorption vapor pressure lowering as a function of temperature. A new steam table can now be produced. The technique involves using Equation 7 to calculate Swcrit. Equation 9 is then used to convert Swcrit to a temperature Tcrit. P/Psat is then calculated for each temperature in the steam table below Tcrit. Note that P/Psat has a minimum value of zero. Finally, the calculated values of P/Psat are multiplied by the corresponding steam table vapor pressure values to produce an adsorption pseudo steam table. Figure 9 is a plot of the standard steam table and the pseudo steam table.
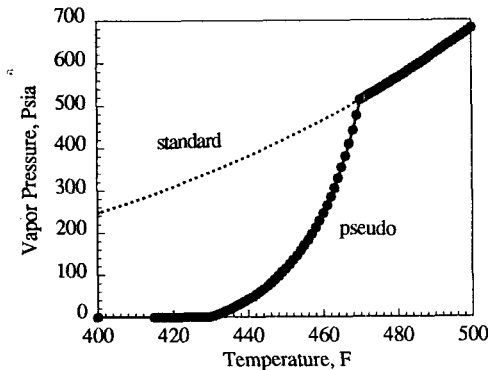

Figure 9 - The standard steam table and the pseudo steam table. Vapor pressure as a function of temperature.

Note that the vapor pressure values in the pseudo steam table are drastically lower than those in the standard steam table. This lowering of vapor pressure approximately accounts for the effect of adsorption.

TETRAD Run with the Pseudo Steam Table

The pseudo steam table shown in Figure 9 was used in place of the standard steam table for a TETRAD test run. This test run is identical to the first TETRAD with the following exception. The pseudo steam table was used in place of the standard steam table in the input deck.

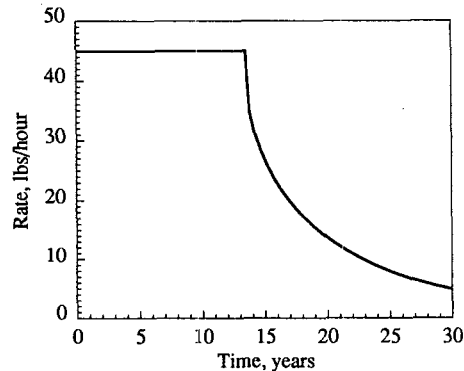The results of this run are shown in Figures 10, 11, and 12.

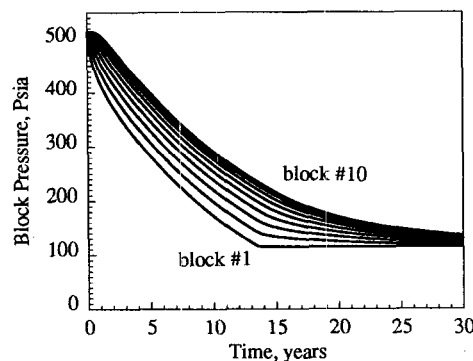**Figure 10** - Rate vs. time for TETRAD with adsorption run.

Figure 11 - Pressure vs. time for each of ten blocks in TETRAD with adsorption run.
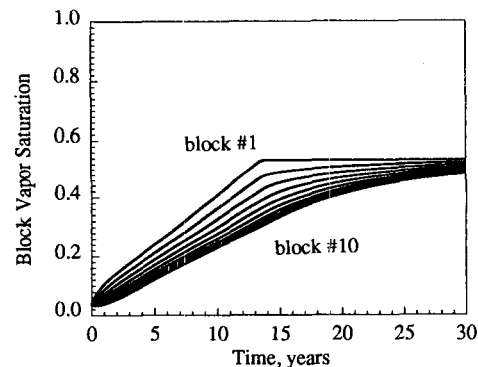

Figure 12 - Steam saturation vs. time for each of ten blocks in TETRAD with adsorption run.

The TETRAD run with the psuedo steam table shows good agreement with the results from the ADSORB run. This can be seen by comparing Figures 10, 11, and 12 with Figures 3, 4, and 5 respectively. The good agreement between these two runs shows that TETRAD can be used to model the effects of adsorption if the steam vapor pressure is reduced judiciously. This pseudo steam table technique although successful, is cumbersome to

employ. This exercise proves, however, that the concept of lowering vapor pressure to model adsorption does indeed produce desired results.

The 'DESORB' Input Card

A new input card, DESORB, has been proposed. Its accompanying algorithm will lower the steam phase partial pressure as a direct function of saturation. The concept of partial pressure classically applies to a multicomponent system. Specifically, if a gas phase consisted of several components, then each component's partial pressure would depend on its relative mole fraction. Typical simulators have a built in framework which allows this type of partial pressure manipulation. Therefore, the proposed modeling technique will use this existing framework.

In geothermal simulation, the partial pressure of steam equals unity because a one component model is usually assumed. To model a desorbing system, the partial pressure of steam will be allowed to vary from 0.0 to 1.0.

When the DESORB card is invoked, the partial pressure of steam will be calculated as a function of liquid saturation using Equations 5, 6, and 7. Depending on liquid saturation, Equations 5, 6, and 7 will return a steam partial pressure between 0.0 and 1.0. This partial pressure will then be multiplied by the standard steam table vapor pressure. This will produce a lowered, adsorption vapor pressure.

The Effect of Thermal Conductivity

In the Tetrad run with the pseudo steam table, all thermal conductivities were set to zero. This was required to allow direct coupling of temperature and saturation. Real systems, however, do have finite thermal conductivities. To investigate the importance of thermal conductivity to the present study, the TETRAD with pseudo steam table run was repeated with normal thermal conductivities. It was found that the inclusion of thermal conductivity had a minor effect on the results. In summary, block number 1, which contained the production well, behaved differently from the previous run. Blocks 2 through 10, however, showed similar behavior to the run which had zero thermal conductivity. This suggests that for this case, the omission or inclusion of thermal conductivity has a stronger effect on the near wellbore vicinity where temperature gradients were largest. It can therefore be said that the inclusion of thermal conductivity does affect the behavoir of the simulation, but it does not nullify the effects of adsorption. It is expected that the thermal conductivity effect will be reduced further when the DESORB partial pressure algorithm is employed.

Conclusions

The TETRAD geothermal simulator, with minor modifications, can be used to model a reservoir producing under desorbing conditions. This can be accomplised by correctly adjusting the steam partial pressure. This process can be performed by a proposed new input card and its accompanying algorithm. A successful test of this method was performed by accordingly lowering the vapor pressure in a steam table used for a test run. This test run matched the behavior expected from a purely desorbing system. A comparison of simulation runs which contained adsorption to ones that did not contain adsorption was made. This comparison showed that adsorption can be expected to affect the production, pressure, and saturation behavior of a desorbing geothermal system. With the DESORB option, adsorption can be included in full scale simulation to explore adsorption's effect on a producing reservoir's overall preformance.

Acknowledgements

References

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(3) Langmuir, I.,"The Constitution and Fundamental Properties of Solids and Liquids," Part I. Solids. J. Amer. Chem. Soc., 38,2221-2295, 1916.

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(5) Nghiem, C.P. and H.J.Ramey Jr.,"One-Dimensional Steam Flow Under Desorption," Sixteenth Workshop of Geothermal Reservoir Engineering, Stanford University, January, 1991