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SIMULATING THE EFFECTS OF ADSORPTION AND CAPILLARY FORCES IN GEOTHERMAL RESERVOIRS

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ABSTRACT

Until recently, geothermal reservoir simulators use flat interface thermodynamics to determine the thermodynamic state of the reservoir. Development of new simulators and the modification of existing ones has now incorporated the physics of curved interface thermodynamics. These simulators account for the effects of sorption and capillary forces.

The simulators GSS and TETRAD were used to simulate the performance of a hypothetical vapor-dominated geothermal reservoir. GSS is a simulator specifically developed to account for adsorption by using adsorption isotherms. On the other hand, TETRAD is a commercial simulator that was modified to account for vapor pressure lowering by using capillary pressure relations.

GSS and TETRAD yielded similar results. Thus, the two formulations being used to account for curved interface thermodynamics are practically equivalent.

Areas for improvement of both GSS and TETRAD were identified. The hysteresis and temperature dependence of sorption and capillary properties are issues that are needed to be addressed.

INTRODUCTION

A big motivation for the study of the effects of adsorption is the 'Geysers Paradox'. Data from The Geysers field (California) suggest that water must be stored in the reservoir as a condensed phase in superheated state. With adsorption and curved interface thermodynamics, it is possible for liquid water and steam to co-exist at a pressure less than the saturation pressure.

The performance of a vapor-dominated geothermal reservoir is strongly effected by adsorption. The adsorbed condensed phase represents most of the fluid mass in the reservoir. Therefore, it sustains production beyond what might be expected for a reservoir filled only with vapor. While this is beneficial in terms of resource longevity, adsorption complicates the analysis of the reservoir since the liquid water is 'invisible'. Furthermore, the effectiveness of water injection to sustain production of a vapor-dominated reservoir may also be affected by adsorption (Horne, et.al., 1995).

Modeling and simulation remain to be the best methods to characterize and predict the performance of geothermal reservoirs. Until recently, reservoir simulators use the flat interface thermodynamics to determine the thermodynamic state of the reservoir. The development of new simulation codes has incorporated the effects of adsorption and curved interface thermodynamics. This study makes use of these 'new' simulators to investigate of the effects of adsorption and capillary forces in the exploitation of geothermal resources.

THEORY

Physical adsorption is the phenomenon in which molecules of steam adheres to the surfaces of a porous medium. This phenomenon is caused mainly by Van der Waals forces. Desorption is the opposite of adsorption; it occurs when the adsorbed phase vaporizes due to pressure reduction (Horne, et.al., 1995). When sufficient deposition has taken place, a capillary interface may form and deposition due to capillary condensation becomes more significant. The transition from adsorption to capillary condensation is continuous. Both mechanisms cause vapor to condense onto the solid surface.

In addition to mass storage, adsorption affects other aspects of geothermal exploitation. The surface between the vapor and the liquid phases in a porous medium is not flat. It is a well recognized phenomenon that the vapor pressure above the curved surface of a liquid is a function of the curvature of the liquid-vapor interface. Thus, curved interface thermodynamics is more appropriate than flat interface thermodynamics. The curvature of the surface gives rise to vapor pressure lowering (VPL), thus allowing liquid and vapor co-exists in equilibrium at pressures that are less than the saturation pressure.

Sorption (adsorption and desorption) and capillary condensation are affected by temperature. The general behavior is that the amount of the adsorbed phase increases as the temperature increases, and vice versa (Shang, et. al., 1993). In experiments being performed in Stanford University, the amount of steam condensing onto rocks is measured as a function of the relative vapor pressure (p_v/p_{sat}). This relationship, which is measured at a specific temperature, is called an adsorption isotherm. The desorption isotherm is measured when the process is reversed and the condensed phase vaporizes as the pressure is reduced.

Experiments show that adsorption and desorption are not reversible processes. Measurements of adsorption and desorption isotherms clearly show hysteresis. Rock heterogeneity effects on capillary condensation and irreversible changes in the rock pore structure during adsorption are the likely causes of this hysteresis (Shang, et.al., 1993). Because of this, the adsorption isotherm is different from the desorption isotherm.

IMPLEMENTATION

There are two main schools of thought about the implementation of curved interface thermodynamics in reservoir simulation. One focuses on capillary pressure while the other focuses on adsorbed mass in reservoir rocks.

The focus on capillary pressure follows the work of Calhoun et. al. (1949). Experimental studies were conducted to measure vapor pressure lowering and capillary retention of water in porous solid. The primary principle being used is given by Kelvin equation:

$$p_c = RT\rho_l\,(1/M_W)\,\ln(p_{sat}/p_v)$$

where R is the universal gas constant, T is absolute temperature, ρ_l is water density, M_W is the water molecular weight, p_{sat} is the equilibrium vapor pressure (from steam table) and p_v is the lowered vapor pressure. In the original formulation, 'p_c' denotes the capillary pressure. In recent published literature, suction pressure (p_{suc}) is defined as numerically equal to p_c but have a negative sign. The term 'suction pressure' is preferred because it is recognized that the phenomenon being observed involves not only capillarity but also adsorption. The suction pressure is the same mechanism that promotes imbibition of water into the pores of dry rocks.

Works by Pruess and O'Sullivan (1992) and Shook (1994) follow this line of thought and are now being implemented on the simulators TOUGH2 (Lawrence Berkeley National Laboratory), STAR (S-Cubed), and TETRAD Version 12 (also known as ASTRO).

The simulator TETRAD (Version 12) was used in this study. TETRAD is a commercial simulator that has been modified to account for VPL. Version 12 of the code uses the generalized VPL algorithm developed in the Idaho National Engineering Laboratory (Shook, 1993). The algorithm follows-up on the earlier work by Holt and Pingol (1992) to modify the standard steam tables to account for VPL.

The other approach follows the work of Hsieh and Ramey (1978). It focuses on the measurement of the amount of adsorbed mass in reservoir rocks. If the dominant mechanism for liquid storage is adsorption, then measurements of sorption isotherms of water on reservoir rocks is deemed necessary.

Experimental data suggest that sorption isotherms follow a Langmuir-type behavior, as described by a modified form of the Langmuir equation:

$$X = d\ \{\ c\ (p_v/p_{sat})\ /\ (1+(c-1)(p_v/p_{sat}))\ \}$$

where the parameters 'd' and 'c' represent the magnitude and the curvature of the adsorption isotherm (Horne, et.al., 1995). The parameter 'X' is the mass adsorbed per unit mass of rock. The quantity (p_v/p_{sat}) is often denoted by the symbol β, referred to as the relative vapor-pressure or the VPL factor. The isotherm which describes the relationship between sorption and relative vapor-pressure accounts for both adsorption and capillary condensation (Figure 1). Work on this approach is being spearheaded by the Stanford Geothermal Program (work synopsis given by Horne et. al. (1995)).

The implementation of this approach into a numerical simulator was accomplished in GSS, a simulator recently developed in Stanford University. GSS was specially developed to take into account adsorption and curved interface thermodynamics (Lim, 1995).

USING GSS AND TETRAD

The data required to incorporate VPL in numerical simulations is either a p_c vs. S_l (liquid saturation) relationship or the X vs. β isotherm. TETRAD requires a p_c vs. S_l relationship (Figure 2) while GSS requires an X vs. β isotherm (Figure 1).

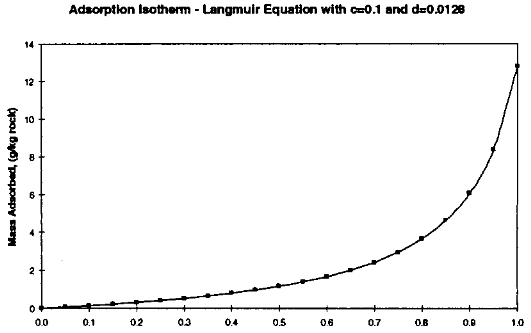

Figure 1: Typical Geysers adsorption isotherm.

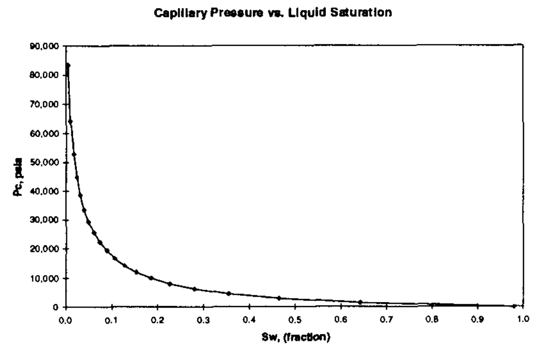

Figure 2: Same adsorption isotherm in Figure 1 converted to p_c vs S_l relationship.

The two sets of data are equivalent and conversion from one to the other is done through the Kelvin equation and an intermediate relation for X vs. S_l. This relation is given by the following equation:

$$S_l = [(1-\phi)/\phi]\ (\rho_r/\rho_l)\ X$$

where ϕ is the rock matrix porosity and ρ_r is the rock grain density.

The resulting p_c vs. S_l relationship can be approximated by the Van Genuchten equation. This equation is expressed as follows:

$$p_c = p_o\ [\ S_{ef}^{-1/\lambda} - 1]^{1-\lambda}$$

where $S_{ef} = (S_l - S_{lr})/(1-S_{lr})$ is the normalized (effective) liquid saturation. The term 'S_{lr}' is the residual liquid saturation (Pruess, et.al., 1992).

Both the Langmuir and the Van Genuchten equations cannot represent the empirical data over the entire range of relative pressure. The Langmuir equation breaks down over the range where the capillary condensation is dominant (e.g. $\beta > 0.9$). On the other hand, Van Genuchten equation breaks down when water saturation is low (e.g., $Sl < 0.1$) where the adsorption effect is dominant. Because of this, even if a simulator has the capability of using data in the form of a parametric equation, it is also important to have the ability to use data in tabular form. Both TETRAD and GSS have this capability.

One of the big advantages of GSS is that it is able to utilize the sorption isotherms from the experiments almost directly. The only data conversion needed is the translation of the isotherm measured in the laboratory to the appropriate reservoir temperature. It must be pointed out that the sorption experiments being conducted by the Stanford Geothermal Program do not exceed 300 °F because of equipment limitations. Actual geothermal reservoir temperature far exceeds this value (i.e. > 450 °F). Although not done in this study, the adsorption isotherm can be translated to the appropriate temperature by recognizing the temperature-invariant relationship between the adsorbed mass (X) and the activity coefficient (A). The activity coefficient is defined as:

$$A = RT\ \ln(1/\beta)$$ (Hsieh and Ramey, 1983).

GSS uses this invariance relation to adjust the adsorption isotherm as the reservoir temperature changes as a result of exploitation (Lim, 1995).

The simplest way to enter a p_c vs. S_l relationship into TETRAD is by using analytical functions of relative permeability and capillary pressure as a function of liquid saturation. However, the built-in analytical expression for capillary pressure,

$$p_c = a\ [1 - S_l]^b$$

where 'a' and 'b' are fitting parameters, is insufficient to represent the converted adsorption data. The Van Genuchten expression is also available but was not used in this study. Instead, tabular input of relative permeability and capillary pressure relations were used.

The main weakness of TETRAD is its inability to adjust the p_c vs. S_l relationship as the reservoir temperature changes in response to exploitation. This is only possible if the built-in analytical expression for capillary pressure is used. This means that the p_c vs. S_l relationship used in this study remains constant even when parts of the reservoir is cooled by production and water injection.

On the other hand, GSS also has problems. First, GSS is not robust. Even with the simple model used in this study, numerical non-convergence was a problem. In particular, the oscillating transition of wells from rate-control to pressure-control is very troublesome. Another major problem is an error in the heat-in-place computation. Comparison of heat-in-place calculated manually, by GSS, and by TETRAD revealed a significant error in GSS.

The common major weakness of GSS and TETRAD is their inability to handle the adsorption/desorption hysteresis (Figure 3). Although any number of sorption isotherms or p_c vs. S_l relationships can be assigned to different matrix blocks, only one sorption isotherm or p_c vs. S_l relationship can be specified for a particular matrix block. The matrix blocks may undergo both adsorption and desorption in response to injection and production operations.

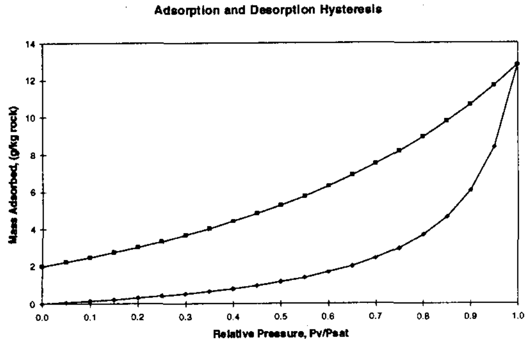

Figure 3: Example of adsorption and desorption isotherms hysteresis.

THE MODEL

A simple generic model of a vapor-dominated reservoir has been developed. The model has dual-porosity. Low permeability matrix blocks provide most of the storage while the fracture system provides the large scale permeability. In its initial state, all liquid saturation resides in the matrix. Relative permeability is defined such that steam is the only mobile phase at the given liquid saturation. Adsorption property is patterned after those typically observed in The Geysers. The data shown in Figure 1 and Figure 2 were used

The model is comprised of horizontal layer 100 feet thick and with dimensions of 1,000 feet on all sides . A uniform 5-by-5 Cartesian grid with a total of 25 gridblocks was used. The geometry of the model is illustrated in Figure 4. The petrophysical properties (porosity, absolute permeability, sorption, and capillarity) for all the 25 fracture blocks and 25 matrix blocks are uniform. Initial thermodynamic state (pressure, temperature, and saturation) are also uniform throughout the model. The properties are given in the table below.

Properties	**Matrix**	**Fracture**
Porosity	4 %	1 %
Permeability	0.01 md	100 md
Liquid Saturation	29 %	0% %
Reservoir Pressure	400 psia	400 psia
Reservoir Temperature	Evaluate	Evaluate
Rock Density	165 lb/ft^3	
Rock Specific Heat	0.245 Btu/lb-°F	
Adsorption Isotherm	c=0.1; d=0.0128 at 500 °F	
Relative Permeability	$k_{rl} = Sw^{*4}$ $k_{rv} = (1-Sw^{*2})(1-Sw^{*})^2$ where Sw* is normalized to Swc=0.35 such that Sw*=(Sw-Swc)/(1-Swc) (Sorey, 1980)	

The appropriate reservoir temperature is evaluated based on the reservoir pressure and the magnitude of the vapor pressure lowering.

Gridblock Dimensions: 200 ft x 200 ft x 100 ft

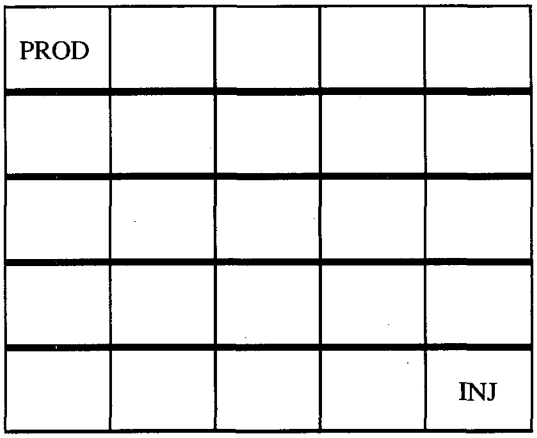

Figure 4: The model used in the simulations.

The model is essentially a 'closed tank'. The model boundaries are closed to mass and heat flows. The only way mass and energy can flow in and out of the systems is though the wells. A production well was placed in one corner of the model and an injection well is placed in the corner diagonally opposite. The maximum production rate of the well is constrained to 10,000 lbs/day. The minimum bottomhole pressure was constrained to 100 psia. The water injection rate is imposed.

The initial state of the model is checked for equilibrium by running the model for 10,000 days without production and injection. Equilibrium is confirmed by the stable thermodynamic properties through time. All of the subsequent predictive simulations are run for 10,000 days. Production and injection operations always begin at day zero and terminate at 10,000 days.

TETRAD VS. GSS - COMPARING RESULTS

The model described above was constructed using both TETRAD and GSS. The TETRAD model and the GSS model are only approximately similar because there are differences in input formats of the two simulators. Zero timestep runs were performed for the models to check the consistency of their initial mass and energy in-place. It was immediately apparent that although the masses in-place are consistent, the energies in-place are not. GSS is computing an initial heat-in-place that is about 33.5% greater than TETRAD's calculation. A manual calculation of the heat-in-place verifies the result of TETRAD. A cursory inspection of the GSS source codes did not reveal an obvious source of error.

It was decided that the heat-in-place discrepancy of the two simulators can be ignored for the purpose of this study. Production and injection rates are low enough such that only a small fraction of the initial heat-in-place will evolve during a 10,000 days simulation (less than 5%). The models were first simulated with production operation only. The objective was to investigate the differences in production, reservoir pressure, reservoir temperature, and matrix water saturation through time with and without VPL.

Without Adsorption/VPL

Figures 5, 6, 7, and 8 shows the results of TETRAD and GSS with the model undergoing production. The thermodynamic state of the model is governed by the flat interface thermodynamics (i.e. no VPL).

Figure 5 shows the comparison of steam production rates though time. The results are practically identical. Both simulators predicted a drastic decline of production as the reservoir dries out at about 6,000 days.

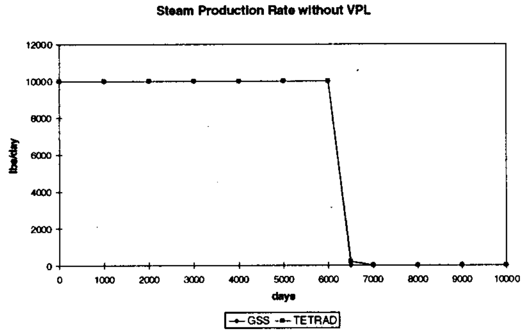

Figure 5: Comparison of steam production rates through time **without** VPL.

Figure 6 shows the comparison of reservoir pressure behavior. After a very gradual decline in reservoir pressure, it declined drastically as the reservoir dried out.

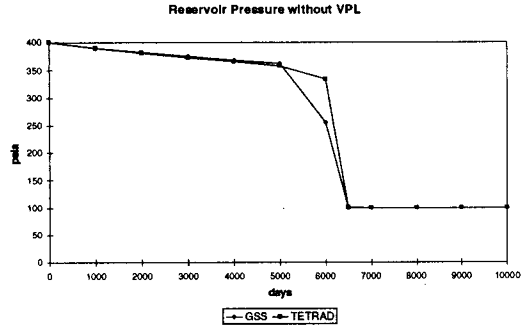

Figure 6: Comparison of reservoir pressure through time **without** VPL.

Figure 7 shows the comparison of reservoir temperature. Although the two models started with the same reservoir temperature of 445 °F (this is the saturation temperature at 400 psia reservoir pressure), significant deviations can be observed in the later stages of the simulation. The GSS model ends up being hotter than the TETRAD model. This temperature deviation can be attributed to the greater heat in-place being calculated by GSS.

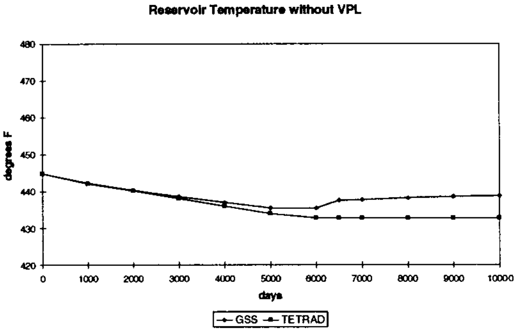

Figure 7: Comparison of reservoir temperature through time **without** VPL.

Figure 8 shows the comparison of matrix water saturation through time. The results are close and show that the reservoir will be completely dry after 6,000 days of production.

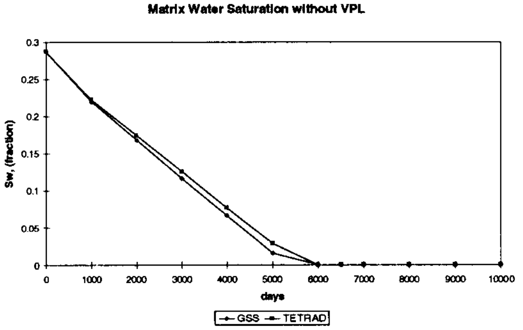

Figure 8: Comparison of matrix water saturation through time **without** VPL.

These results show the classic behavior of a system governed by flat interface thermodynamics. Gradual productivity decline followed by catastrophic decline when the reservoir dries out are expected. The complete dry-out of the matrix is also an expected behavior. Ignoring the obvious discrepancy in heat-in-place and reservoir temperature, for the purpose of this study the TETRAD and GSS models can be considered equivalent.

With Adsorption/VPL

Figures 9, 10, 11, and 12 illustrate the results of TETRAD and GSS with the model undergoing production and the state of the system is governed by curved--interface thermodynamics (i.e. with VPL).

Figure 9 shows the comparison of steam production rates though time. The results are quite close. Both simulators predicted a decline of well productivity starting at about 5,000 days. Note that the decline was observed about 1,000 days earlier than the previous case.

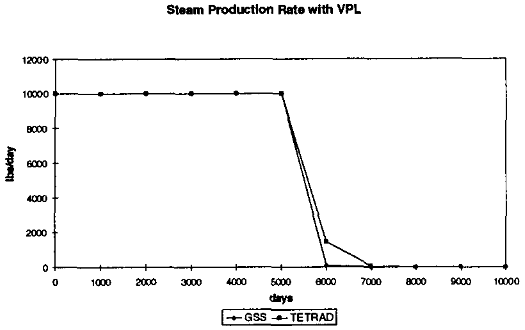

Figure 9: Comparison of steam production rates through time **with** VPL.

Figure 10 shows the comparison of reservoir pressure behavior. The results shows a continuous gradual decline of reservoir pressure until the abandonment pressure of 100 psia was reached.

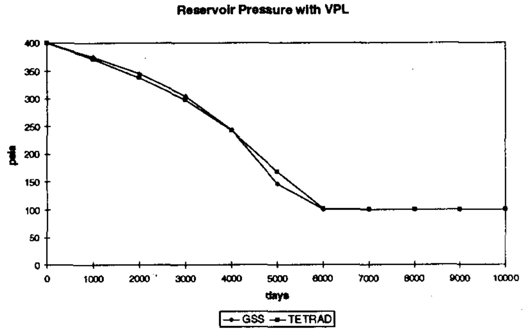

Figure 10: Comparison of reservoir pressure through time **with** VPL.

Figure 11 shows the comparison of reservoir temperature. Again the two models started with the same reservoir temperature. However, the initial reservoir temperature is 466 °F, not the original 445 °F. With VPL, maintaining the reservoir pressure at 400 psia will require a higher temperature than what saturated condition dictates. This implies that the model with VPL is no longer equivalent to the original model without VPL in terms of initial heat-in-place. Comparing TETRAD and GSS, significant deviations can again be observed in the later stages of the simulation. This temperature deviation is again attributed to the greater amount of heat-in-place being calculated by GSS.

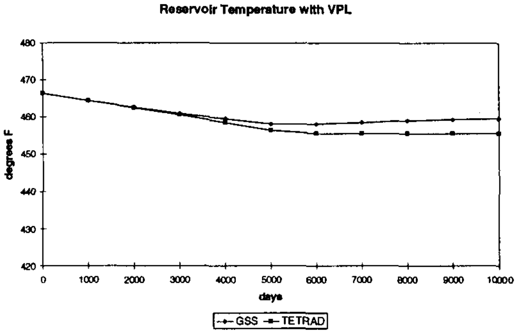

Figure 11: Comparison of reservoir temperature through time **with** VPL.

Figure 12 shows the comparison of matrix water saturation through time. The results are again close and it shows that the reservoir will never completely dry-out. With an abandonment pressure of 100 psia, about 2.5% water saturation will be retained in the rock matrix.

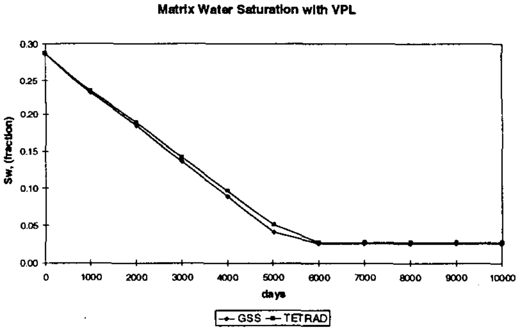

Figure 12: Comparison of matrix water saturation through time **with** VPL.

MODELING INJECTION

The ability to model the effects of water injection into vapor-dominated reservoirs is of great interest to the industry. Experience has shown that vapor-dominated systems are prone to run out of working fluid (water) even though vast amount of heat still remain in the reservoir. It was established through research and field studies that water injection into the reservoir can provide artificial mass recharge to improve steam production from the field (Enedy, et.al, 1991). However, if done incorrectly injection may have detrimental effects on production (Barker, et.al., 1991). Clearly, an appropriate injection program is a major component of resource management for vapor-dominated systems.

Modeling injection with a numerical simulator is inherently challenging. The equations for two-phase fluid and heat flow processes are highly non-linear. Order-of-magnitude changes in fluid properties, relative permeability, capillarity, gravitational instability of water over steam, and viscous instabilities at the water-vapor interface are some of the causes of non-linearity. A reliable and robust simulator is required to model injection (Pruess, 1995).

Simulations using GSS were conducted to investigate the effect of injection if adsorption and capillary condensation are considered. The model was modified such that the production well have a low productivity index. At peak production rate, a pressure drop of about 200 psi is incurred between the formation and wellbore. The main reason this was done was to increase the contrast between production performance of models with and without VPL. A pair of production and injection wells (as described previously) was used. Injection rates ranging from 0 to 100% of peak production rate (10,000 lbs/day) were used. The production performances through time with 0% to 60% injection are shown in Figure 13.

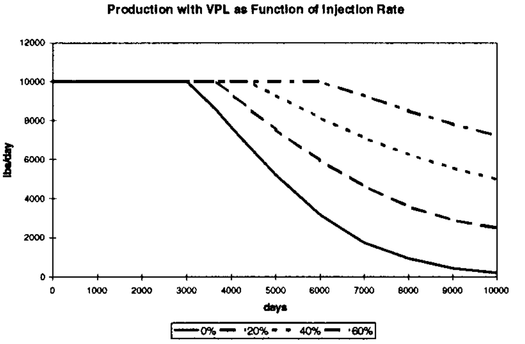

Figure 13: Comparison of well production for different injection rates.

Injection into the reservoir supported production such that higher cumulative production is recorded by the end of simulation at 10,000 days. However, it is apparent that the incremental gain in steam production declines with higher injection rates (Figure 14). If mass recovery is plotted versus the rate of injection, it can be seen that effective recovery is reduced at higher injection rates (Figure 15). Mass recovery is defined as the cumulative mass produced divided by the sum of the initial mass in-place and the injected mass. If there is no injection, mass recovery is 86%. With an injection rate equal to 100% of peak production, the mass recovery is reduced to 61%. However, it must be pointed out that the un-produced mass is still available for production if the simulation is extended beyond 10,000 days.

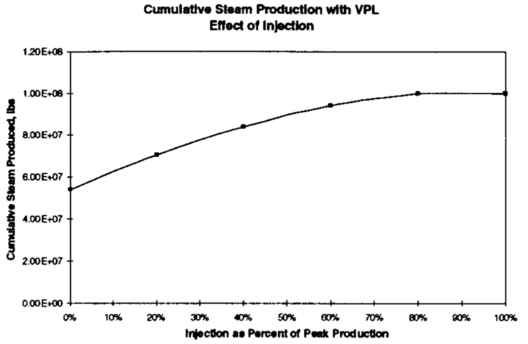

Figure 14: Cumulative steam production at 10,000 days in response to different injection rates.

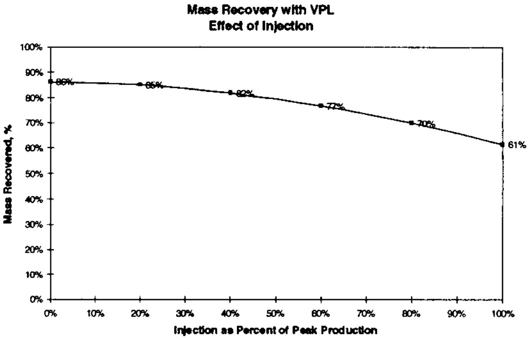

Figure 15: Mass recovery at 10,000 days in response to different injection rates.

For comparison, simulation runs with no VPL were also conducted. With injection rates ranging from 0% to 20% of peak production, the same model predicts 98 to 99% mass recovery.

DISCUSSION OF RESULTS

One of the most revealing result of this study is the inter-dependence of pressure, temperature, and saturation within the environment of a geothermal reservoir. With flat interface thermodynamics, water saturation in the rock matrix is a quantity that is independent of pressure and temperature for a system in saturated condition. Because saturation was really one of the big unknown quantities in reservoir modeling, its arbitrariness gave it a reputation of a "calibrating" parameter. However, with curved-interface thermodynamics this is no longer the case. If the measured reservoir pressure and temperature are close to saturation condition, this implies that VPL is negligible and a high liquid saturation is appropriate. On the other hand, if a substantial vapor pressure lowering (i.e., superheat) is observed, liquid saturation must be small and it can be evaluated if the sorption properties of the reservoir rocks are known.

Adsorption and desorption hysteresis is a major issue that needs to be addressed. Sorption experiments in Stanford University using cores from The Geysers show that the adsorption and desorption isotherms can be very different. For reservoirs with low liquid saturation, the hysteresis can cause water to be retained in the rock matrix instead of becoming available for production. This will have a big impact when predicting the effects of injection. In the preceding simulations, although it was assumed that adsorption and desorption follow the same isotherm, it was already apparent that the water retention property of the reservoir rock is already significant. It is a hypothesis that increased injection rate causes localized increase in reservoir pressure, thus promoting adsorption rather than production of the injected water. If an actual desorption isotherm was used, water retention will be further increased, therefore resulting to an even lower mass recovery from injection operations.

Capillary or suction pressure is a major factor affecting the propagation of injectate into the reservoir. The high magnitude of suction pressure (in the order of 10^4 psi) of rocks with low water saturation will cause injectate to be imbibed into the rock matrix, away from the high permeability fractures. If injection is targeted in depleted areas with high degree of superheat, imbibition of water into the rocks may minimize the detrimental effects to production that is associated with injection breakthrough. When injecting water, heat transfer limitation is always the biggest issue. If injectate can be sucked away from the high permeability flow channels (fractures), it will facilitate the development of a sustainable injection program.

CONCLUSIONS

The results of this study suggest that adsorption and capillary forces are major factors governing the behavior of a vapor-dominated geothermal reservoir. These mechanisms affect both the resource size estimation and the production performance of the field. Furthermore, the effectiveness of water injection programs in sustaining the geothermal field's productivity is also affected.

Geothermal reservoir simulators that honor curved interface thermodynamics are now available. Simulators with formulations based on either sorption isotherms or capillary forces yield equivalent results.

Hysteresis and temperature dependence of sorption and capillary properties are issues that still need to be addressed. These processes should be incorporated in future codes of geothermal reservoir simulators.

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