

EFFECTS OF CAPILLARITY AND VAPOR ADSORPTION IN THE DEPLETION OF VAPOR-DOMINATED GEOTHERMAL RESERVOIRS

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INTRODUCTION

Vapor-dominated geothermal reservoirs in natural (undisturbed) conditions contain water as both vapor and liquid phases. The most compelling evidence for the presence of distributed liquid water is the observation that vapor pressures in these systems are close to saturated vapor pressure for measured reservoir temperatures (White et al., 1971; Truesdell and White, 1973). Analysis of natural heat flow conditions provides additional, indirect evidence for the ubiquitous presence of liquid. From an analysis of the heat pipe process (vapor-liquid counterflow) Pruess (1985) inferred that effective vertical permeability to liquid phase in vapor-dominated reservoirs is approximately 10^{-17} m^2 , for a heat flux of 1 W/m^2 . This value appears to be at the high end of matrix permeabilities of unfractured rocks at The Geysers, suggesting that at least the smaller fractures contribute to liquid permeability. For liquid to be mobile in fractures, the rock matrix must be essentially completely liquid-saturated, because otherwise liquid phase would be sucked from the fractures into the matrix by capillary force. Large water saturation in the matrix, well above the irreducible saturation of perhaps 30%, has been shown to be compatible with production of superheated steam (Pruess and Narasimhan, 1982).

In response to fluid production the liquid phase will boil, with heat of vaporization supplied by the reservoir rocks. As reservoir temperatures decline reservoir pressures will decline also. For depletion of "bulk" liquid, the pressure would decline along the saturated vapor pressure curve, while for liquid held by capillary and adsorptive forces inside porous media, an additional decline will arise from "vapor pressure lowering."

Capillary pressure and vapor adsorption effects, and associated vapor pressure lowering phenomena, have received considerable attention in the geothermal literature, and also in studies related to geologic disposal of heat generating nuclear wastes, and in the drying of

porous materials. Geothermally oriented studies were presented by Chicoine et al. (1977), Hsieh and Ramey (1978, 1981), Herkelrath et al. (1983), and Nghiem and Ramey (1991). Nuclear waste-related work includes papers by Herkelrath and O'Neal (1985), Pollock (1986), Eaton and Bixler (1987), Pruess et al. (1990), Nitao (1990), and Doughty and Pruess (1991). Applications to industrial drying of porous materials have been discussed by Harmathy (1969) and Whitaker (1977).

This paper is primarily concerned with evaluating the impact of vapor pressure lowering (VPL) effects on the depletion behavior of vapor-dominated reservoirs. We have examined experimental data on vapor adsorption and capillary pressures in an effort to identify constitutive relationships that would be applicable to the tight matrix rocks of vapor-dominated systems. Numerical simulations have been performed to evaluate the impact of these effects on the depletion of vapor-dominated reservoirs.

CAPILLARY SUCTION, VAPOR ADSORPTION, AND VAPOR PRESSURE LOWERING

Thermodynamic analysis shows that for pure single-component fluids such as water, coexistence of liquid and vapor phases at any given temperature T is possible only for a certain unique pressure, which is termed the saturated vapor pressure, or saturation pressure, $P_{\text{sat}}(T)$. The thermodynamic properties of liquid and vapor, and the conditions under which these phases can coexist, are altered inside porous media by interfacial forces between rock minerals and fluids (Edlfsen and Anderson, 1943; Calhoun et al., 1949; Philip, 1978; Udell, 1982). Liquid water wets rocks preferentially compared to vapor and is held by adsorptive forces as a thin layer of a few molecular thicknesses on the rock surfaces (He, Cushman, and Diestler, 1987). In addition, liquid water is held by capillary forces in the smaller pores. Both liquid adsorption and capillarity cause liquid phase pressure P_l to be lower than vapor phase pressure P_v ; the difference

$$P_l - P_v = P_{\text{suc}} < 0 \quad (1)$$

is termed the suction pressure, P_{suc} . In most of the literature, the difference in phase pressures is referred to as "capillary pressure" P_{cap} which is given by

$$P_{\text{cap}} = -\frac{2\sigma\cos(\alpha)}{r} \quad (2)$$

Here σ is the surface tension of the wetting phase, α is the contact angle, and r is the mean radius of curvature of the capillary meniscus. We prefer the more general term suction pressure because this is not limited to a specific mechanism, such as capillarity. Experimentally one measures a suction pressure that results from the combined effects of capillarity and adsorption. The suction exerted on the liquid phase diminishes its tendency for vaporization. Vapor pressure above a liquid held by capillary or adsorptive forces is therefore reduced in comparison to vapor pressure above the flat surface of a bulk liquid. The reduction is expressed in terms of a vapor pressure lowering factor, or relative vapor pressure, β , defined by

$$\beta = P_v/P_{\text{sat}}(T) \quad (3)$$

The relationship between β and P_{suc} is given by the Kelvin equation

$$\beta = \exp\left[\frac{M_{\text{H}_2\text{O}} P_{\text{suc}}}{\rho_l R(T+273.15)}\right] \quad (4)$$

where $M_{\text{H}_2\text{O}}$ is the molecular weight of water, ρ_l is liquid phase density, R is the universal gas constant, and temperature T is measured in °C. β depends chiefly on suction pressure, which in turn is primarily a function of liquid saturation, S_l . At typical vapor-dominated conditions of $T = 240^\circ\text{C}$, the suction pressures required for 1%, 10%, and 20% vapor pressure lowering (i.e., β equal to 0.99, 0.90, and 0.80) are, respectively, -19.4 bars, -203 bars, and -430 bars. Thus, significant reduction in vapor pressure will occur only for very large suction pressures.

The Kelvin equation establishes a connection between adsorption of vapor on porous materials, and the suction pressure experienced by the adsorbed liquid phase: When vapor at a pressure $P_v < P_{\text{sat}}$ is brought in contact with a porous medium, adsorption and capillary condensation will take place until a liquid saturation S_l is established such that the corresponding suction pressure P_{suc} satisfies Equations (3) and (4). The results of vapor adsorption experiments are usually given in terms of mass of adsorbed vapor X_v per mass of porous material, as function of relative vapor pressure β . (Some authors measure adsorbed mass in molar rather than mass units.) Assuming that the density of the adsorbed phase is close to that of liquid water, the corresponding saturation of adsorbed liquid phase can be calculated as

$$S_l = \frac{X_v (1-\phi) \rho_R}{\phi \rho_l} \quad (5)$$

Here ϕ is the porosity of the medium, and ρ_R is rock grain density. Equations (4) and (5) can be used to convert adsorption data of X_v versus β to an equivalent suction pressure relationship, S_l versus P_{suc} .

EXPERIMENTAL DATA

Several different experimental techniques are available for measuring suction pressure and vapor adsorption characteristics of porous materials (summarized by Evans, 1983). Suction pressures can be obtained through direct measurement or control of the pressure difference between wetting and non-wetting phases, or through mercury intrusion experiments with subsequent scaling for surface tension and contact angle. Vapor pressure lowering effects can be measured through thermocouple psychrometry, or through vapor pressure measurements for known amounts of adsorbed vapor. Where different techniques could be employed to measure suction pressures and/or vapor pressure lowering in overlapping regimes, consistent results have been obtained (Melrose, 1988). Illustrative data from the literature are given in Figures 1 and 2 in the form of mass fraction of water adsorbed (or held by capillarity) vs. relative vapor pressure $\beta = P_v/P_{\text{sat}}$; the data sources are summarized in Table 1. Some of the same data are replotted in Figure 3 in the form of liquid saturation vs. suction pressure (see Equations 4 and 5).

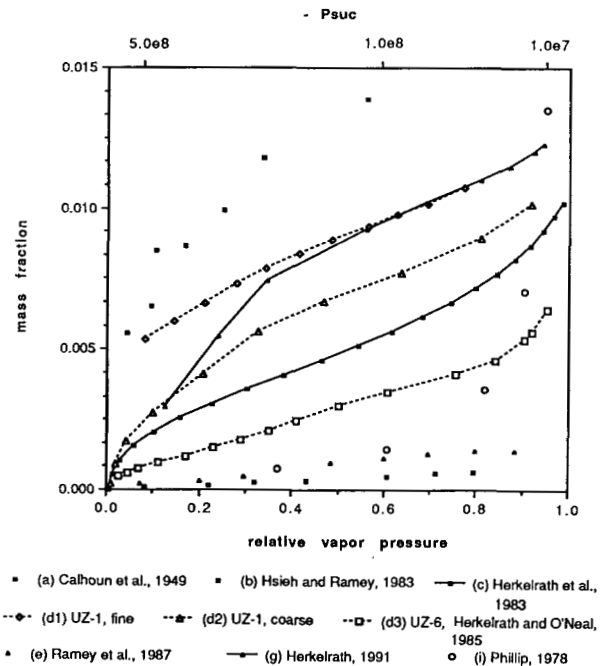


Figure 1. Data on vapor adsorption from different literature sources.

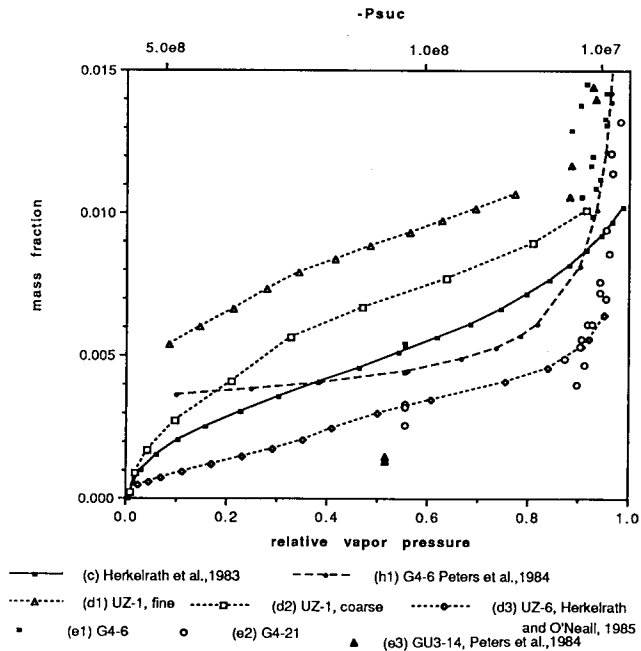


Figure 2. Another collection of literature data on vapor adsorption.

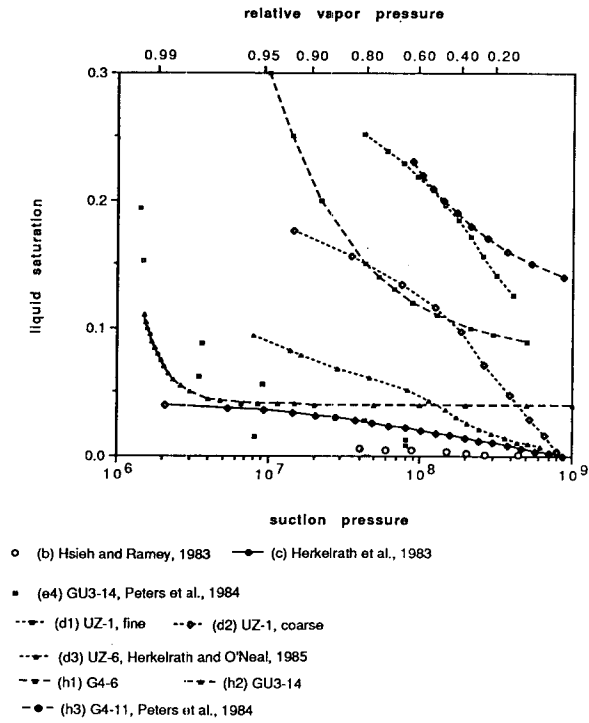


Figure 3. Liquid suction pressure characteristics for different geologic materials.

Table 1. Literature data on vapor adsorption and liquid suction

Reference	Experimental Sample	Measurement
Calhoun et al., 1949	manufactured consolidated quartz	(a,c) 36°C
Hsieh and Ramey, 1983	Berea sandstone	(c) 146°C
Herkelrath et al., 1983	unconsolidated natural sand	(c) 100, 125, 146°C
Peters et al., 1984	welded and nonwelded tuffs from Yucca Mountain	(b,d) ambient T
Herkelrath and O'Neal, 1985	Topopah Spring welded tuff	(c) 100°C
Ramey et al., 1987	cores from The Geysers	(c) 180, 200°C
Herkelrath, 1991	graywacke from The Geysers	(c) 100°C

- (a) direct measurement of water suction pressure
- (b) mercury intrusion
- (c) vapor adsorption measurement
- (d) vapor pressure lowering by thermocouple psychrometry

From Figures 1-3 it is apparent that geologic media display a great diversity of vapor pressure lowering and suction pressure relationships, which reflects the tremendous diversity in the distribution of pore sizes, and in the composition and activity of mineral surfaces. Suction pressures are generally stronger for tight media with small pores.

A number of theoretical formulae have been suggested for calculating the quantity of water adsorbed on solid surfaces. The simplest, credited to Langmuir (1916), is

$$X_v = \frac{\beta}{a+b\beta}. \quad (6)$$

Here a and b are fitting parameters. Nghiem and Ramey (1991) used (6) to obtain a good match to the Topopah Spring welded tuff data of Herkelrath and O'Neal (1985), and to unpublished vapor adsorption measurements by Herkelrath on graywacke samples from The Geysers (also made available for the present study).

The BET formula (Brunauer, Emmett and Teller, 1938) has also been used to match adsorption data. This formula can be written in the form

$$X_v = \frac{c\beta x_m}{(1-\beta)[1+(c-1)\beta]}, \quad (7)$$

with fitting parameters c and x_m . Hsieh and Ramey (1978) used Equation (7) to obtain an excellent fit to the data of Calhoun et al. (1949). Herkelrath and O'Neal (1985) obtained a good fit to Topopah Spring welded tuff data using a BET curve in the range $0 < \beta < 0.35$.

Herkelrath et al. (1983) obtained a good fit to data for unconsolidated material, containing sand, silt and clay, using the empirical formula

$$\beta = A(10^{[-10^{(B-S_v/C)}]}) \quad (8)$$

Here A , B , and C are fitting parameters.

In an extensive study Peters et al. (1984) measured suction pressure vs. mass fraction of water adsorbed for a number of samples of tuffaceous materials from Yucca Mountain, Nevada. They converted each measurement of mass fraction of water adsorbed into an equivalent liquid saturation and were then able to obtain reasonable fits to their data with van Genuchten's expression (1980), which we write in the form

$$P_{suc} = -P_o \left[S_{ef}^{-1/\lambda} - 1 \right]^{-\lambda}, \quad (9)$$

where

$$S_{ef} = \frac{S_l - S_{lr}}{1 - S_{lr}}. \quad (10)$$

Here P_o and λ are fitting parameters and S_{lr} is the residual liquid saturation. While providing a good fit to the data of Peters et al. (1984) over most of the suction pressure range, the van Genuchten expression Equation (9) tends to overpredict liquid saturation at large suction pressures. The Langmuir and BET formulae (Equations (6) and (7)) also cannot fit the data over the complete range. They do not have the correct shape to give the rapid decline in adsorbed mass as the relative vapor pressure decreases below 1.0. It appears that the van Genuchten expression is most applicable to the capillary regime of weaker suction pressures, while the Langmuir or BET equations describe the adsorptive regime of strong suction.

There is considerable variation in the shape of the curves and the values of the fitting parameters for samples from similar materials. This seems to be related mainly to the variation of porosity and therefore perhaps to the balance between capillary and surface adsorption effects. The data given by Peters et al. (1984) cover a much wider range than most of the data shown in Figures 1 and 2. In particular some large porosity samples gave much larger values for adsorbed mass. However, few of the samples gave values of adsorbed mass lower than those depicted by the points labeled e1, e2 and e3 in Figure 2. The data given by Hsieh and Ramey (1983) and Ramey et al. (1987) stand out as very low, with adsorbed mass well below all the other experiments.

Figure 3 shows some of the same data as in Figures 1 and 2 converted, using Equations (4) and (5), to give S_l as a function of P_{suc} . Also best fit van Genuchten curves for some of the data from Peters et al. (1984) are plotted. These plots clearly show the problem with the van Genuchten curves. They approach a finite liquid saturation as suction pressure tends to infinity. To fit the data well a two stage function would be required which drops rapidly near $-P_{suc} = 10^6$ Pa and then declines more slowly towards zero at large $-P_{suc}$. Possibly the rapid initial drop is associated with capillary effects and the subsequent drop is associated with surface adsorption. In the numerical simulations, below, we have avoided the infinity in P_{suc} by employing a cutoff of $-P_{suc} \leq 5000$ bars.

Although the range of different suction behavior is large, it is seen that significant reduction of vapor pressure, 10% say, will occur only for rather small liquid saturations of the order of 20% or less. Vapor pressure lowering effects will be unimportant for reservoir processes at higher liquid saturations.

NUMERICAL SIMULATIONS

From a phenomenological viewpoint, capillarity and adsorption can be viewed as mechanisms that tend to retain fluid in the reservoir, making it less accessible to extraction. In practical circumstances, other fluid retention mechanisms will be present as well. For example,

fluid reserves may be stored in matrix rocks of low permeability, from which they can only slowly discharge to the fracture system to become available for production. Fluid retention will cause a more rapid pressure decline when producing at prescribed rates, and a more rapid rate decline when producing at prescribed pressures.

We have performed numerical simulations to examine and evaluate the nature and strength of fluid retention from capillarity and adsorption. The calculations were performed with LBL's general-purpose simulator TOUGH2, which implements the general MULKOM architecture for coupled multiphase fluid and heat flows (Pruess, 1983, 1991). TOUGH2 models vapor pressure lowering effects by means of the Kelvin equation (4). Our first simulation examines constant-rate production from a zero-dimensional "lumped-parameter" reservoir model (single grid block). In this case there is no flow in the reservoir; all of the fluid reserves are equally accessible to production, and differences in depletion behavior for cases with and without vapor pressure lowering are solely due to differences in the thermodynamic properties (vapor pressure, enthalpy of vaporization) between "free" water (no VPL) and water held by capillary or adsorptive forces (VPL). Subsequently we simulate distributed-parameter models to examine VPL effects on flow processes.

For the illustrative calculations in this paper we have used the suction pressure relationship obtained by Peters et al. (1984) for their sample G4-6, employing a cutoff of $-P_{\text{suc}} \leq 5000$ bars. This is a tight welded tuff with a permeability of $1.9 \times 10^{-18} \text{ m}^2$ (1.9 microdarcies), which may be representative of the tight reservoir rocks of The Geysers. Apart from providing a reasonable fit to suction pressure characteristics over a wide range, the van Genuchten curves have the advantage that they permit a consistent evaluation of liquid relative permeability from Mualem's model (1976) in closed form:

$$k_{rl} = \sqrt{S_{ef}} \left[1 - (1 - S_{ef}^{1/\lambda})^\lambda \right]^2 \quad (11)$$

S_{ef} is defined in Equation (10). Gas (vapor) phase relative permeability was assumed as $k_{rg} = 1 - k_{rl}$. Other parameters used in the simulations are summarized in Table 2. Additional parameter specifications are given in the presentation of the different cases, below. Initial reservoir temperature in all cases was near 240°C.

Thermodynamic Effects

We consider a zero-dimensional reservoir of 1 km^3 volume, with an initial liquid saturation of 80% and a pressure of 33.44 bars, corresponding to a saturation temperature of 239.93°C. No permeability specifications are needed in this problem because the reservoir is modeled as a single grid block. Production occurs at a constant rate of 34.37 kg/s, which at initial fluid reserves of $32.716 \times 10^9 \text{ kg}$ (without VPL effects; when VPL is included, initial reserves are $32.691 \times 10^9 \text{ kg}$) can be sustained for 30.16 years. The system is taken through 20 depletion steps of 1.5 years each, and simulated pressures, temperatures, and liquid saturations with and without VPL are given in Table 3.

The reservoir with VPL effects starts off with a temperature that is slightly higher (0.44°C) than the reservoir without VPL, in order to attain the same vapor pressure as in the no VPL system. Temperatures and liquid saturations for depletion with and without VPL are seen to remain very close at all times. Differences in reservoir pressures are small at early times, reaching 0.7 bars at 50% depletion (15 years), 2.7 bars at 75% depletion (22.5 years), and becoming very large as ultimate dry-up with extremely strong suction pressures and VPL effects is approached. Thus, VPL effects are insignificant for most of the productive life of the system.

Table 2. Formation parameters for simulation problems

rock grain density	2600	kg/m ³
rock specific heat	920	J/kg.°C
formation thermal conductivity	2.51	W/m°C
matrix porosity	5%	
matrix permeability (*)	10^{-18}	$5 \times 10^{-18} \text{ m}^2$
formation permeability (&)	$5 \times 10^{-14} \text{ m}^2$	
formation compressibility	0	bar ⁻¹
suction pressure data: van Genuchten fit of Peters et al. (1984) for welded tuff sample G4-6, with parameters		
λ	= 0.4438	
S_{lr}	= 0.0801	
P_o	= $1.727 \times 10^6 \text{ Pa}$	

(*) Block depletion problem.

(&) Radial flow to a well.

Table 3. Depletion of zero-dimensional reservoir

Time Step	Time (yrs)	Pressure (bars)		Temperature (°C)		Liquid Saturation (%)	
		VPL	No VPL	VPL	No VPL	VPL	No VPL
	0	33.44	33.44	240.37	239.93	80	80
1	1.5	32.69	32.73	239.15	238.72	75.76	75.77
2	3	31.95	32.04	237.94	237.15	71.55	71.56
3	4.5	31.21	31.34	236.71	236.28	67.36	67.37
4	6	30.48	30.66	235.48	235.05	63.19	63.20
5	7.5	29.74	29.98	234.24	233.81	59.04	59.05
6	9	29.01	29.32	233.00	232.57	54.91	54.92
7	10.5	28.28	28.66	231.74	231.31	50.80	50.81
8	12	27.54	28.00	230.48	230.05	46.72	46.73
9	13.5	26.80	27.36	229.21	228.78	42.65	42.66
10	15	26.03	26.72	227.94	227.51	38.61	38.61
11	16.5	25.24	26.09	226.66	226.23	34.59	34.58
12	18	24.40	25.47	225.37	224.94	30.59	30.58
13	19.5	23.47	24.86	224.07	223.64	26.62	26.59
14	21	22.36	24.25	222.77	222.34	22.68	22.62
15	22.5	20.90	23.66	221.46	221.03	18.77	18.66
16	24	18.49	23.07	220.15	219.71	14.95	14.73
17	25.5	12.71	22.49	218.87	218.38	11.33	10.81
18	27	1.62	21.92	217.64	217.05	8.00	6.92
19	28.5	1.57	21.35	216.23	215.71	4.13	3.04
20	30.0	1.53	7.66	214.82	214.56	0.28	0

Depletion of Tight Matrix Blocks

Most of the fluid reserves in vapor-dominated systems are stored in tight matrix blocks with permeability of order 1 microdarcy (10^{-18} m^2). The fracture system is believed to contribute little to fluid storage, but provides large-scale permeability. We have simulated fluid production from tight matrix blocks under conditions considered representative for the depletion of vapor-dominated systems such as The Geysers and Larderello.

The model system (see Figure 4) consists of a single block of rock matrix in the shape of a cube with side length $D = 50 \text{ m}$, which is to be viewed as a subdomain of a large reservoir volume. Matrix permeability is of order 10^{-18} m^2 , and matrix porosity is 5%. The block is surrounded by fractures which are assigned an arbitrary (small) fractional volume of 10^{-4} . Initial conditions are a pressure of 33.44 bar throughout, and liquid saturation of 80% in the matrix block, 1% in the fractures, respectively. Liquid relative permeability is taken as the van Genuchten form (Equation (11)) with parameters identical to those obtained by Peters et al. (1984) for the suction pressure relationship of sample G4-6. Gas relative permeability is assumed as $k_{rg} = 1 - k_{rl}$.

Depletion is initiated by placing a "well" on deliverability in the fractures. Well specifications are a bottomhole pressure of 10 bars, and a productivity index of $1.788 \times 10^{-13} \text{ m}^3$. For the depletion simulation the

matrix block is discretized according to the MINC method (Pruess and Narasimhan, 1982, 1985) with 9 nested cubes, using the following volume fractions (from outside to inside): 2%, 4%, 6%, 8%, 10%, 13%, 16%, 20%, and 21%. For matrix permeabilities of 1 and $5 \times 10^{-18} \text{ m}^2$, three different cases were simulated: (Case 1) including both suction pressure and VPL effects, (Case 2) including suction pressures but no VPL effects, and (Case 3) "conventional" approach, neglecting capillary- and adsorption-induced suction pressures (and consequently neglecting VPL effects as well).

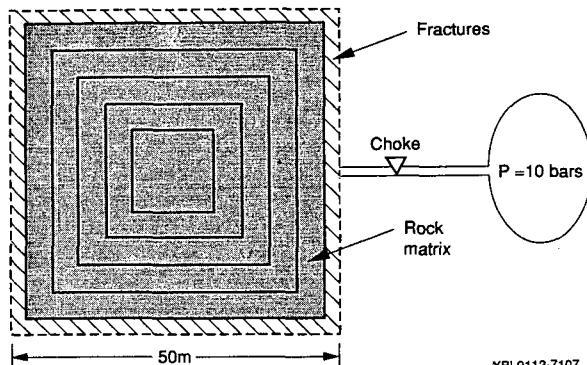


Figure 4. Schematic of matrix block depletion problem, with MINC discretization.

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Depletion proceeds at high rates of mass discharge initially, and then slows down as discharge rates from the block decline in response to declining pressures and fluid mobilities (Figure 5). Relative to Case 3 (no suction pressures), introduction of suction pressures (Case 2) introduces an additional force for driving liquid towards the matrix block surface, where suction pressures are strongest because of diminishing liquid saturation from vaporization. Therefore, Case 2 yields generally higher flow rates and a more rapid depletion than Case 3 (Figures 5 - 7).

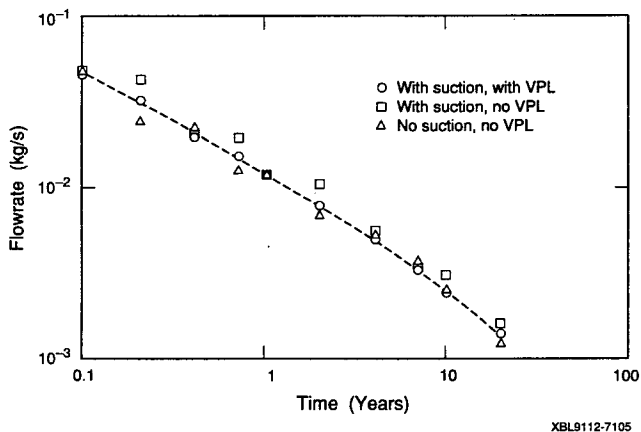


Figure 5. Simulated time dependence of flow rates in block depletion problem for matrix permeability of 10^{-18} m^2 .

The effect of vapor pressure lowering (Case 1) is to accelerate pressure decline as fluid discharge proceeds from the block, diminishing the driving force for vapor outflow from the block, and consequently slowing depletion of fluid reserves. For the parameters used here, this effect tends to approximately cancel the increase in depletion rate from suction pressure effects, so that the depletion behavior in Case 1 is very similar to that in Case 3. The effects from suction pressures and vapor pressure lowering are rather modest. Total produced mass in Case 2 is approximately 20% larger at all times than cumulative production in Case 3 (Figure 6). For a matrix permeability of 10^{-18} m^2 , cumulative production in Case 1 exceeds that of Case 3 by typically 5% or less. Produced enthalpies are virtually identical in all cases, being 2.88 MJ/kg ($\pm 0.5\%$) for times greater than 0.1 years. For the larger matrix permeability of $5 \times 10^{-18} \text{ m}^2$ fluid recovery is more rapid (Figure 7), but the differences between the Cases 1, 2, and 3 are again modest and very similar to those for the tighter matrix block.

From Figure 5 it is seen that in Case 1 (with VPL) there is a very smooth dependence of flow rate on time, while in the no VPL and no P_{suc} cases periodic excursions are superimposed on the overall trend of declining flow rates. The excursions reflect discretization effects: flow rates are controlled by the pressure of the outermost grid block that is still in two-phase (boiling) conditions, and pressures there are constrained to be equal to

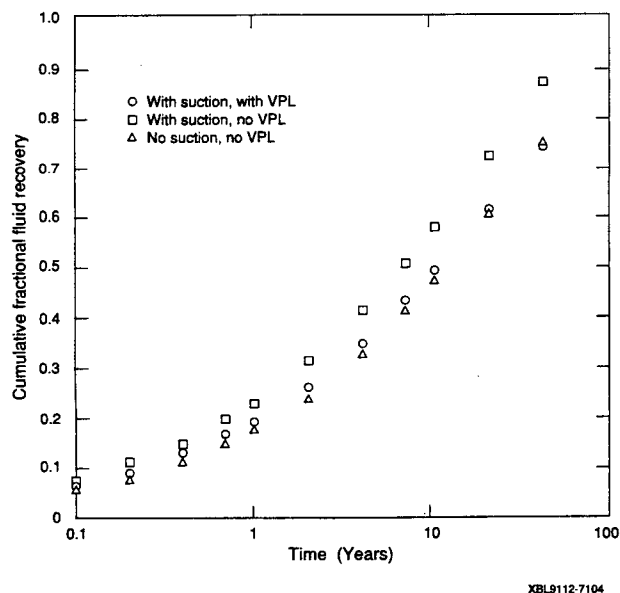


Figure 6. Cumulative fluid recovery in block depletion problem for matrix permeability of 10^{-18} m^2 .

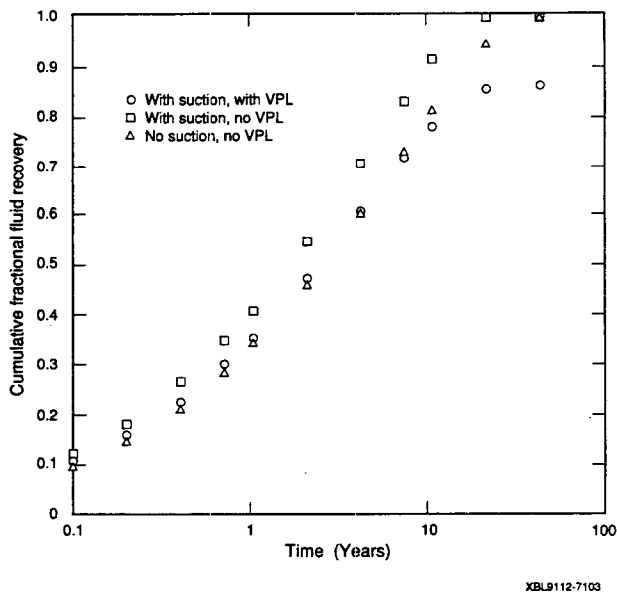


Figure 7. Cumulative fluid recovery in block depletion problem for matrix permeability of $5 \times 10^{-18} \text{ m}^2$.

saturation pressure at prevailing temperature. Every time a grid block dries out pressure control "jumps" to the next block towards the interior of the matrix, with a discrete jump in path length for vapor flow and associated drop in flow rate. Inclusion of VPL effects removes the strict correspondence between temperature and pressure in two-phase conditions. Vapor pressure decreases gradually as liquid saturation declines. Thus, from a numerical simulation viewpoint, vapor pressure lowering has the beneficial effect of broadening what otherwise would be a sharp phase front between single-phase vapor and two-phase conditions.

Radial Flow to a Well

To evaluate the possible impact of VPL effects on well testing in superheated vapor zones we model flow to a production well in one-dimensional radial geometry. We consider a cylindrical reservoir with a large radius of 10 km, a thickness of $H = 1000$ m, and permeability of $50 \times 10^{-15} \text{ m}^2$, for a total permeability-thickness product of $50 \times 10^{-12} \text{ m}^3$ (50 darcy-meters). Effective well radius is assumed as $r_w = 10$ m which, for a well of 0.2 m diameter (8 inches), corresponds to a skin factor of $s = -4.605$, typical for fractured wells. Initial reservoir conditions are a temperature of 240°C and a pressure of 10 bars, corresponding to highly superheated steam. According to the Kelvin equation, this vapor pressure corresponds to a liquid suction pressure of -2328.2 bars, for which the G4-6 characteristic curve of Peters et al. (1984) gives a liquid saturation of 9.848%. A comparison case without VPL effects was also simulated; this has zero liquid saturation (single-phase vapor) because $P_v < P_{sat}$. The reservoir is discretized into 100 grid blocks with radial increments logarithmically increasing from $\Delta r_1 = 1$ m. Production occurs at a

constant rate of 5 kg/s. Relative permeabilities are assumed equal to 1 for gas, 0 for liquid, regardless of saturation.

Figure 8 shows results for calculations with and without VPL effects, plotted as pressure-squared versus the logarithm of the similarity variable t/r^2 (O'Sullivan, 1981). In each case results for two different times fall on the same curve, confirming the similarity variable t/r^2 . With the exception of small values of t/r^2 , the data fall very accurately on semilog straight lines. Both straight lines have the same slope of 14.7 bar^2 per log-cycle in t/r^2 . Using the asymptotic solution for radial gas flow (Matthews and Russel, 1967)

$$P_i^2 - P(r,t)^2 = \frac{q_m \mu}{2\pi k H} \frac{zR(T+273.15)}{M_{H_2O}} \times \left[\ln \frac{t}{r^2} + \ln \frac{k}{\phi \mu c} + 0.80907 \right] \quad (12)$$

this slope translates into a permeability-thickness product of $kH = 49.93 \times 10^{-12} \text{ m}^3$, in excellent agreement with the value of $50 \times 10^{-12} \text{ m}^3$ used in the simulation. In Equation (12) P_i is initial pressure, q_m is mass flow rate, μ is viscosity, z the real gas compressibility factor, and c is total (fluid plus formation) compressibility. From the t/r^2 values at which the extrapolated straight lines reach the initial pressure $P_i^2 = 100 \text{ bar}^2$ we obtain from Equation (12) values for fluid compressibility of $c = 3.95 \times 10^{-6} \text{ Pa}^{-1}$ with VPL and $c = 1.30 \times 10^{-6} \text{ Pa}^{-1}$ without VPL. Thus it is seen that VPL effects increase effective fluid compressibility relative to single-phase vapor. However, fluid compressibility with VPL is smaller than typical two-phase compressibility without VPL (Grant and Sorey, 1979).

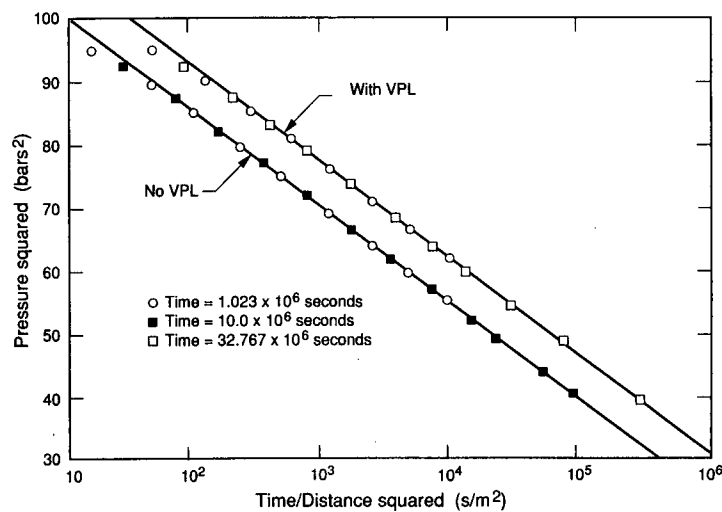


Figure 8. Semilog plot of pressure-squared in radial flow problem.

DISCUSSION AND CONCLUSIONS

Capillarity, vapor adsorption on rock surfaces, and vapor pressure lowering are interrelated and strongly coupled effects. Different geologic media show a tremendous variety of capillary and adsorptive behavior. Although existing data are insufficient for a detailed quantitative description of vapor pressure lowering effects in vapor-dominated reservoirs such as The Geysers and Larderello, a survey of literature data indicates that VPL effects will become significant (reducing vapor pressure by 10% or more) only at low liquid saturations of 20% or less. Initial liquid saturations in vapor-dominated systems are believed to be large, in excess of 80% and most likely close to 100% (Pruess and Narasimhan, 1982; Pruess, 1985), so that VPL effects on production rates and pressures will be negligible for most of the productive life of vapor-dominated systems, playing a role only in the final stages of reservoir dry-out.

Depending on the relative permeability behavior of vapor-dominated systems, which has not yet been well characterized, it is possible that the suction effects from capillarity and vapor adsorption may significantly affect liquid flow in the matrix blocks. While of minor importance for pressure and flow-rate behavior of vapor-dominated systems, the presence of adsorbed and capillary water at pressures below saturated values may play a crucial role in rock-fluid reactions, and in the release and transport of non-condensable gases.

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