22
7-14-75
2 Sept 1975

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the laboratory.

UCID - 16791

LAWRENCE LIVERMORE LABORATORY

University of California/Livermore, California

**THE EFFECT OF SALINITY ON
GEOTHERMAL WELL PERFORMANCE**

J. Z. Grens

May 14, 1975

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Prepared for U. S. Atomic Energy Commission under contract no. W-7405-Eng-48

MASTER
DISTRIBUTION OF THIS DOCUMENT UNLIMITED
fig

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

The effect of varying concentration of dissolved solids on the wellflow characteristics and energy yield of geothermal wells is considered. Increasing salinity is found to have an adverse effect on well production and on the energy content of the fluid produced. This effect may reach a 0.8 to 0.9% reduction in available energy for each 1.0% dissolved solids. Simple techniques for estimating the physical and thermodynamic properties of brines as functions of composition and temperature are also presented.

THE EFFECT OF SALINITY ON GEOTHERMAL WELL PERFORMANCE

J. Z. Grens

INTRODUCTION

Geothermal resources vary widely in the concentration of dissolved solids present in the reservoir fluids. This variation spans three orders of magnitude¹; at the upper end of the range are the high-salinity brines of the Salton Sea geothermal area of California, with 250,000+ ppm.

Dissolved solids strongly affect the fluid's energy content and availability and the performance of the producing wells. As salinity increases, changes occur in physical properties (density, viscosity) and thermodynamic properties (vapor pressure, heat capacity, enthalpy).

This report describes methods for estimating some brine properties and the magnitudes of their effect on wellflows and power-generating capacity, at salinities typical of Salton Sea geothermal fluids.

THERMODYNAMIC PROPERTIES

Vapor Pressure

At very low solute concentrations, the vapor pressure of water over aqueous solutions can be adequately described by Raoult's Law:

$$P = P_0(\text{mol frac.}), \quad (1)$$

which simply states that the vapor pressure over the solution (P) is equal to the vapor pressure of approximately pure water at the same temperature (P_0) multiplied by its mole fraction. For highly concentrated electrolyte solutions, however, serious deviations occur. Keevil² has determined these deviations for NaCl and KCl, and they are essentially linear up to 0.15 mole fraction dissolved salts.

The following expression adequately describes the vapor pressure of aqueous solutions of NaCl and KCl to saturation and 593 K (300°C):

$$P = P_0[1.0 - 2.2(\text{mol frac.})_s], \quad (2)$$

where $(\text{mol frac.})_s$ is the mole fraction dissolved solids. For Salton Sea brines, $(\text{mol frac.})_s$ may be computed using an average molecular weight of 76.0 for the salts (see Table 1). Figure 1 shows vapor pressure curves computed using Eq. 2 compared to data given by Helgeson³ and Hass,⁵ who gives a much more accurate (and more complex) method for vapor pressure estimation.

Table 1. Composition of Salton Sea area geothermal brines.

Compound	Molecular weight	Well designation (reference)					
		#2-IID (3)		#1 State (3)		#4 Sinclair (4)	
		ppm $\times 10^{-3}$	Wt. fr. total chlorides	ppm $\times 10^{-3}$	Wt. fr. total chlorides	ppm $\times 10^{-3}$	Wt. fr. total chlorides
KCl	74.55	31.46	0.128	26.69	0.129	34.32	0.141
NaCl	58.44	134.72	0.548	121.51	0.587	131.76	0.561
CaCl ₂	110.98	79.75	0.324	58.7	0.284	72.82	0.298
Average molecular wt.		77.52		75.44		76.37	

Enthalpy

The enthalpy of concentrated geothermal brine is difficult to estimate accurately. One common rule⁶ combines the enthalpies of the pure components of the system in a linear manner. For example, in a solution with a mass fraction x of solute,

$$H_t = H_w(1 - x) + H_s x,$$

in which H_t , the enthalpy of the solution, is simply the sum of the enthalpies of the water fraction $H_w(1 - x)$ and the salt $H_s x$. Salt enthalpy can be conveniently computed from an average heat capacity of 0.2 cal/(gm·K) for geothermal brines.

Although this technique is rather crude, it checks reasonably well with data given by Daley⁷ for seawater concentrates to 500 K and 24% salinity and with enthalpies given by Helgeson for geothermal brines.

Vapor enthalpy is a function of state only (P, T) and can be obtained directly from steam tables.⁸

Entropy

The entropy of the solution can be estimated in a manner analogous to that used for enthalpy. Again, errors are incurred by neglecting the heat of solution of the salts and their variation with temperature, but comparison with Daley's data indicates a small error at temperatures of interest.

Fig. 1. Vapor pressure of salt solutions.

Table 2. Density of NaCl solutions in Mg/m^3 for various temperatures and salinities (from Ref. 9).

Temperature, K (°F)	NaCl Salinity (wt%)					
	0	5	10	15	20	25
373 (212)	0.958	0.993	1.029	1.065	1.104	1.144
423 (302)	0.917	0.953	0.990	1.028	1.067	1.106
473 (392)	0.865	0.904	0.944	0.984	1.024	1.063
523 (482)	0.799	0.844	0.889	0.933	0.977	1.019
573 (572)	0.712	0.767	0.820	0.874	0.927	0.977

PHYSICAL PROPERTIES

Density

The density of NaCl solutions as a function of temperature and salinity are also given by Hass⁹ to an accuracy of better than 0.25%. Sufficient accuracy for estimation can be obtained by linear interpolation from Table 2. For greater accuracy, the generating equations described in the original work⁹ may be used.

Viscosity

The viscosity of a 25% NaCl brine is about double that of water for temperatures to 473 K. At temperatures above 443 K (70°C), 25% CaCl_2 brines are less viscous than water. Therefore, the viscosity of water should represent the mixed chloride brines reasonably well, particularly for the compositions typical of the Salton Sea area.

WELL PERFORMANCE

The performance of a geothermal brine well, and hence, the influence of salinity upon it, must be evaluated on the basis of the total available energy in the wellhead product. Factors influencing this total can be placed in two categories: the energy extraction process, and the thermodynamic state and properties of the wellhead product.

The first category, the energy extraction process itself, is essentially independent of the salinity of the working fluid (thermodynamic factors being grouped in the second category), but it must be considered to obtain a basis for appraising salinity effects on well productivity.

The Energy Extraction Process

Energy can be extracted from the geothermal brine by a number of methods, including heat exchange to a secondary fluid, separation of a steam fraction at some pressure for use in a turbine, or use of the total wellflow to drive a turbine. Austin et al.¹⁰ has compared these techniques and concludes that a total flow turbine has a substantial advantage in energy extraction over other techniques. This conclusion is valid, since any system which rejects a portion of the well product at a temperature above the heat rejection temperature of the conversion process is in effect rejecting a fraction of the available energy.

The turbine isentropically expands wellhead product through a nozzle to condenser pressure/temperature. In this expansion, thermal energy is converted to kinetic energy of the fluid stream:

$$\Delta H_s = \frac{V_2^2}{2gc} - \frac{V_1^2}{2gc}, \quad (4)$$

in which ΔH_s is the enthalpy change in isentropic expansion and V is the fluid velocity. The kinetic energy is converted to mechanical energy by the turbine wheel.

While neither the nozzle nor the wheel actually operate with 100% efficiency, a meaningful appraisal of the effect of salinity on available energy can be made on the basis of an ideal turbine, assuming only that salinity will not affect the actual efficiency.

For evaluating well performance, then, we will consider the energy available from an isentropic expansion to condenser conditions. The condenser pressure will be taken as the vapor pressure of water, 11.7 kPa (1.7 psia) at the available cooling water temperature of 322 K (120°F).

The Wellhead Product

The flow of brine and steam from a geothermal well is essentially an adiabatic process; i.e., no heat is transferred to or from the fluid during its progress up the wellbore. In addition, no work other than the pressure-volume work associated with the flow is done upon the fluid. For these conditions, the first law of thermodynamics may be written for a mass of fluid (m) stationary at a base height (Z):

$$-\Delta H = m \frac{\Delta V^2}{2} + mg\Delta Z . \quad (5)$$

Since the kinetic energy at the wellhead is less than the excess energy stored in the compressed liquid brine for wells 1554 m (5100 ft) deep and velocities less than 127 m/sec (420 ft/sec), it is reasonable to ignore it.

For a given set of in situ conditions (P_0 , T_0 , X_0 , Z_0), Eq. (5), together with an equation of state and thermodynamic properties of the fluid, defines the locus of all possible wellhead conditions.

As an example, consider a geothermal well such as that described by Austin et al.¹⁰:

Depth	1554 m (5100 ft)
Static well bottom pressure	15.3 MPa (2213 psia)
Well bottom temperature	573 K (572 °F)
Well diameter	24.4 cm (9-5/8 inch)

The enthalpy of the well fluid (ignoring liquid compression) will vary with salinity from 1.34 MJ/kg (577 BTU/lb) for pure water to 1.06 MJ/kg (458 BTU/lb) at 25.8% dissolved salt. The locus of wellhead product compositions on a pressure quality diagram will then follow lines of constant enthalpy, as shown in Fig. 2.

The energy available in an isentropic expansion to 11.7 kPa (1.7 psia) can be calculated for all points on the pressure quality diagram. It should be noted, however, that if a direct contact condenser is used, the final pressure will be fixed by the vapor pressure of relatively pure cooling water, but the final temperature of the expansion will be fixed by the equation of state of the well product, and will approach 327 K (130 °F). A surface condenser will reach the same temperature in all cases, with lower pressures occurring in the case of high-saline brines.

Figure 3 shows the variation of available energy per unit mass of fluid with wellhead pressure for pure water and 25.8% brine. The figure was prepared on the basis of direct contact condensation and 100% turbine efficiency.

Wellflow Considerations

In passing from the reservoir through the wellbore to the surface, the pressure of the geothermal fluid is reduced by several processes:

1. Reservoir pressure drawdown,
2. Frictional pressure losses in the well,
3. Hydrostatic pressure loss,
4. Pressure loss due to acceleration.

Fig. 2. Pressure-quality diagram for isenthalpic expansion.

Fig. 3. Enthalpy change in isentropic expansion to 1.17 kPa (1.7 psia).

Item (1) is essentially a source impedance, while items (2) to (4) are recognized as components of the mechanical energy balance for vertical flow:

$$\frac{dP}{\rho} + \frac{VdV}{\alpha g_c} + \frac{g}{g_c} dz + \frac{2fcV^2 dz}{g_c D} = 0. \quad (6)$$

It is convenient to examine each term separately for the effect of fluid salinity and flow pattern before proceeding to overall wellflow calculations.

Reservoir Drawdown

The decrease in well bottom pressure as fluid is withdrawn from the well is referred to as drawdown, and is one of the most important factors in computing wellflows. Unfortunately, it is also very difficult to predict. It is affected by formation permeability, fluid viscosity, and well diameter. For comparison, measured drawdowns for Salton Sea brine wells as given by Helgeson³ will be used. From this data, Austin¹⁰ has developed a relation for drawdown:

$$P_d = Kw, \quad (7)$$

in which P_d is the pressure loss at the well bottom, w is the mass flow, and K is an empirical constant. For P_d in kPa (psi) and w in kg/sec (lb/sec), K equals 24.3 (1.6). Drawdown accounts for about 25% of the difference between static pressure at the well bottom and wellhead pressure at 2465 kg/m³·sec (500 lb/ft²·sec).

Frictional Losses

Fluid friction with the pipe wall is another major consideration. For the case of homogeneous, turbulent flow, friction loss is given by:

$$\frac{dP}{dz} = \frac{2fCV^2}{g_c D} \quad (8)$$

in which f is the well-known Fanning friction factor.*

For non-homogeneous flow of liquid plus vapor, other more complex techniques, such as that of Ros¹² can be used, but since friction amounts to only about 20-25% of pressure losses in a flowing well at 500 lb/sec ft² and application of the Ros¹² correlation indicates only about a 10% change in friction losses, a homogeneous flow model is adequate.

Salinity has an effect on friction loss due to the increase in fluid density, but the effect never exceeds 10%.

* Equation (8) defines f , values of which can be obtained from Moody¹¹ and others. The factor f should not be confused with friction factors defined by other relations.

Hydrostatic Losses

For the case of a vertically flowing homogeneous fluid, hydrostatic losses are simply:

$$dP_h = \rho_z dz \quad (9)$$

Hydrostatic losses account for over 50% of the wellbore pressure loss in a well flowing $2465 \text{ Kg/m}^2 \cdot \text{sec}$ ($500 \text{ lb/sec} \cdot \text{ft}^2$). Increasing salinity affects these losses by increasing ρ and by reducing the vapor pressure so that flashing occurs higher in the wellbore.

Increases in density and decreases in vapor pressure account for most of the effects on wellhead conditions shown in Fig. 4.

In this case of two-phase flow, some holdup of the more dense phase occurs, increasing the hydrostatic pressure gradient. Again, the Ros¹² technique can be applied to estimate the two-phase hydrostatic gradient. At $2465 \text{ kg/m}^2 \cdot \text{sec}$ ($500 \text{ lb/ft}^2 \cdot \text{sec}$) from the standard well, the total excess gradient due to holdup is approximately 0.172 MPa (25 psi) at the wellhead.

Kinetic Energy Effects

Although pressure losses due to acceleration of the fluid are generally small, they are included for completeness:

$$DP_{ke} = \frac{\rho V dV}{g_c \alpha} \quad (10)$$

In Eq. 10, α is the correction for non-uniform velocity profile, about 0.8 to 0.9 for turbulent flow.¹³ Again, for the standard well at $2465 \text{ kg/m}^2 \cdot \text{sec}$ ($500 \text{ lb/ft}^2 \cdot \text{sec}$), ΔP_{ke} totals 34.5 kPa (5 psi) at the wellhead.

WELLFLOW CALCULATION

Calculation of wellhead conditions for the typical geothermal well previously described is straightforward. For a chosen mass flow, bottom hole conditions are calculated by Eq. 7. The mechanical energy balance, [Eq. 6], overall energy balance [Eq. 5], and the equation of state for water (modified for salinity), are applied to finite vertical elements until the wellhead is reached.

The calculation is carried out on a small digital computer, using polynomial generating functions to provide physical and thermal properties. The approximations described at the beginning of the report are used to estimate brine properties.

Fig. 4. Pressure-flow curves for typical well at $f = 0.012$.

An example of the variation of wellhead pressure and temperature with mass flow and salinity is shown in Fig. 4. This figure was produced using a friction factor of 0.012, which is probably too high for pure water in steel casing, but is appropriate for the scale layers which will form in a casing carrying flashing brine. The important feature of this calculation is the reduction in wellhead pressure with increasing salinity.

ENERGY YIELD

The energy available from the wellflow can be determined by combining the results of the wellflow calculation (P, Q) as given in Fig. 4 with the energy available from isentropic expansion, ΔH , as shown in Fig. 3:

$$\text{Wellhead Energy} = (Q)_p \cdot (\Delta H)_p \quad (11)$$

The result of such a combination is shown in Fig. 5. Again, this result is for a hypothetical well operating with a friction factor of 0.012.

Figure 5 illustrates that

- The available energy is significantly lowered by increasing salinity (22% at 0.25 weight fraction salts),
- The pressure at which maximum energy per unit well area is obtained is somewhat lower.

SUMMARY

In a typical well flowing a nominal $2465 \text{ kg/m}^2 \cdot \text{sec}$ ($500 \text{ lb/ft}^2 \cdot \text{sec}$), pressure losses are distributed roughly 1/4 to formation drawdown, 1/4 to friction, and 1/2 to hydrostatic loss. The higher density and lower vapor pressure which accompany increasing salinity both tend to add to the hydrostatic gradient in the flowing well. Two phase flow effects in the wellbore are primarily those associated with holdup of liquid relative to vapor, adding a few percent to the hydrostatic gradient.

Energy yield is affected by both the reduced energy available from solutions of increasing salinity and by the adverse effects of salinity on wellflow. As a first approximation, each 1% dissolved solids reduces available energy by 0.8 to 0.9%, compared to pure water at the same in situ temperatures and pressure.

The distribution of pressure losses will vary with formation properties, in situ conditions and well parameters. The examples given pertain to a typical well in the high-salinity region of the Salton Sea, and should be applied to greatly differing regions or well configurations only with extreme care.

Fig. 5. Effect of salinity on available energy per unit well area. (Hypothetical standard well - see text.)

REFERENCES

1. P. Kruger and C. Otto, Geothermal Energy (Stanford University Press, 1973).
2. N. B. Keevil, J. Am. Chem. Soc. **64**, 841 (1942).
3. H. C. Helgeson, Am. J. Sci. **266**, 129 (1968).
4. J. H. Hill, Lawrence Livermore Laboratory, private communication.
5. J. L. Hass, Jr., Economic Geology **66**, 940-946 (1971).
6. R. H. Perry, et al., Chemical Engineers Handbook (McGraw-Hill, New York, 1973), 5th ed.
7. J. G. Daley, W. E. Hilding, and D. A. Fisher, "Thermodynamic Properties of Seawater Concentrates," Proceedings of the 5th Symposium on Thermophysical Properties, Newton, Mass., Oct. 1970, p. 134.
8. J. H. Keenan and F. G. Keyes, Thermodynamic Properties of Steam (Wiley, New York, 1936).
9. J. L. Hass, Jr., Am. J. Sci. **269**, 489 (1970).
10. A. L. Austin, G. H. Higgins, and J. H. Howard, Total Flow Concept for Recovery of Energy from Geothermal Brine, Lawrence Livermore Laboratory, Rept. UCRL-51366 (1973).
11. L. F. Moody (Translator), ASME **66**, 671 (1944).
12. N. C. J. Ros, J. Petroleum Tech. **13**, 1037 (1961).
13. G. W. Govier and K. Aziz, The Flow of Complex Mixtures in Pipes (Van Nostrand, New York, 1972).

NOTICE

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research & Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights."

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$ *; Microfiche \$2.25

<u>* Pages</u>	<u>NTIS Selling Price</u>
1-50	\$4.00
51-150	\$5.45
151-325	\$7.60
326-500	\$10.60
501-1000	\$13.60