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A TWO-PHASE FLOW APPROACH TO CALCULATE PHYSICAL-CHEMICAL PARAMETERS OF GEOTHERMAL RESERVOIR FLUID

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SUMMARY I present, an approach to calculate the fluid thermodynamic parameters; chemical speciation, pressure and temperature, in a geothermal reservoir from the parameters measured in the geothermal fluid (vapor and liquid) at the well separator. In steady state flow condition, the laws of conservation of mass and total (mechanical and thermal) energy are used with the assumption of no heat loss or gain due to thennal conduction. The frictional pressure drop in the well is also neglected with respect to gravitational and accelerational pressure drops. It is necessary to measure pressure and temperature independently at the well head and the separator for dealing geochemistry of the system correctly.

1. INTRODUCTION:

Fluid geochemistry is a valuable tool in the evaluation of energy prospects of geothermal systems in the exploration and exploitation stages. It is used to determine various reservoir parameters such as temperature, state of water-rock interaction, fluid flow pattern, recharge zone, size of the reservoir, etc. The effect of the cooling processes of the fluid during ascent to the surface due to heat conduction and admixtures with cold waters or steam losses may be evaluated by means of changes introduced in the chemical and isotopic composition (Giggenbach et al, 1983). In order to obtain these reservoir parameters and to evaluate reservoir processes from fluid chemistry, various theoretical approaches have been developed, but the first step in these approaches is to determine the deep reservoir fluid composition from fluids separated water and steam obtained from drilled wells and/or natural manifestations using the principles of conservation of energy and mass.

In these calculations it is assumed that vapor and water are always in thermodynamic equilibrium in tlie well as well as in the steam-water separator. The enthalpy of geothermal fluid is considered as a conservative quantity (Henley et al, 1984). In this article it will be discussed that these assumptions are not always valid in case of geothermal systems. A systematic approach will be developed to calculate geochemical composition of the fluid, pressure and temperature in the reservoir which are the fundamental quantities to deal any type of geochemical problem. We use the conservation of mass and total energy (mechanical and thermal energies), and a simplified two phase flow model. The effects of non-condensable gases in the vapor phase and dissolved solutes in liquid phase are not taken into account on the physical properties of solution in these calculations. In other words the properties of pure water and vapor are used.

2. RESERVOIR PARAMETERS CALCULATION METHODS:

The bottom of the well is, generally, fed with compressed liquid that reaches after passing through the permeable strata of the reservoir. As the liquid (geothermal fluid) flows up in the well, it suffers a pressure drop caused by gravitational, frictional, and accelerational effects. At some elevation along the well, the local fluid pressure falls to the saturation pressure corresponding to the fluid temperature, and boiling begins. This elevation is called the 'flash horizon'. Beyond this point, the fluid exists as a mixture of liquid and vapor of successively greater quality (Michaelides and Shafaie, 1986). In the separator the mixture is separated into vapor and water at a specified pressure (or temperature). The separated water is flashed in the weirbox at atmospheric pressure. The samples of water after the weirbox and steam after the separator are, generally, collected to analyze geochemical parameters.

Firstly, the existing approach is summarized which is based on conservation of mass and thermal (enthalpy) energy. Till now, it is a common practice to measure only the well head and separator pressures (or temperatures) as the thermodynamic equilibrium between water and vapor is assumed at every stage of the well flow. So either of them (pressure or temperature) is considered sufficient to describe the system thermodynamically, however, this is not always true in case of a geothermal system. Finally, the theoretical concepts used in the approach with the two-phase flow model and conservation of mass and total energy will be discussed.

2.1 Conservation of mass and thermal energy

This approach is well documented by Henley et al (1984). Any conservative quantity (total mass of any element or isotope, or any extensive thermodynamic quantity) may be used to write a material or energy balance equation. With using the assumption of equilibrium between water and vapor in the well and in the separator one can write the energy (enthalpy) balance equation as

$$H_R = y \cdot H_v + (1-y) \cdot H_l \qquad \text{..... 1}$$

where y is the fraction, by weight, of vapor in the separator, and H_R is the total discharge enthalpy which is determined from the separator pressure (or temperature) and the flow rates of steam and water at the separator (Grant et al, 1982). This quantity is commonly known as reservoir fluid enthalpy in describing the geochemistry of a geothermal system. It is usually assumed that there is only water in the reservoir. The H_v and H_l are the enthalpy of vapor and water, respectively, at the pressure in the separator, which can be read out from the saturated vapor steam-table at the separator pressure. Thus from H_R, H_l, and H_v the fraction of vapor (y) can be calculated.

Similarly the distribution of any species (C_R) in the reservoir fluid between vapor and liquid phase (C_v and C_l) in the separator can be written as

$$C_R = y \cdot C_v + (1-y) \cdot C_l \qquad \text{..... 2}$$

These are the two equations with three unknown (y, C_l, and C_v). To determine the concentration of a species in the reservoir the experimental distribution coefficient for the species at the separation pressure needs to be known and it is defined as

$$B = \frac{C_v}{C_l} \qquad \text{..... 3}$$

In case of the isotopic species we deal with the isotopic ratio (less abundant to more abundant) and the distribution coefficient is named as fractionation coefficient.

The concentration of any species is measured analytically either in the vapor phase from the separator or in the liquid phase from the weirbox. To calculate the concentration in liquid at the separator from the weirbox liquid phase concentration the above equations 1, 2 & 3 are used with slight modifications as the liquid of separator is separated in vapor and liquid at atmospheric conditions.

The above calculations were made assuming a single phase (liquid) in the reservoir which is not always the case. To obtain the fraction of steam at the feeding zone of a geothermal well Henley et al (1984) present an approach to compare the measured enthalpy (H_R) with the enthalpies corresponding to the temperatures obtained with silica (quartz) and Na-K-Ca geothermometers. They called this fraction of vapor "excess steam" and the enthalpy associated with this steam "excess enthalpy" in the reservoir. Giggenbach (1980) presented a more complicated approach to determine this excess steam using the distribution of gaseous components (such as methane, hydrogen, carbon dioxide and vapor). Nieva et al (1984) modified this approach for the case of high concentration of volatile species other than steam in the vapor phase.

2.2 Two phase flow method

The earlier method is based on the two fundamental assumptions: ***equilibrium between vapor and water in the well*** and ***conservation of enthalpy.*** These assumptions are not always valid in the case of a geothermal system. The existence of superheated steam has been predicted in various geothermal reservoirs, but to my knowledge the production chracteristics even the steam producing wells is not reported in the literature. It is clear thermodynamically that the wells which have superheated steam at the bottom, should also produce superheated steam at the well head. So, one has to measure both temperature and pressure at the separator and the well head, and use the steam table for compressed liquid and superheated steam to deal the geochemistry of the system, correctly. In case of wells which produce mixture of vapor and liquid, one can still assume the existence of equilibrium between the vapor and the liquid as there are usually no data on temperature and pressure measured independently in a geothermal well. So, it is still possible to use saturated steam table for the thermodynamic data of water.

Enthalpy is not a conservative parameter in geothermal systems. The fluid entering at the bottom of a well has practically no velocity, so it does not have any kinetic energy. But the measured high flow rate of steam and separated water after the separator is a direct indication of high kinetic energy of the fluid at the well head. Similarly as the fluid ascending to surface its potential energy increases. So the heat energy changes to mechanical energy (potential and kinetic energies). Hence the total energy must be used as a conservative quantity not the enthalpy in dealing geochemistry of a geothermal system.

The steady state flow and no heat loss with conduction in the well are assumed in this approach, too. As the liquid (geothermal fluid) flows up in the well, it suffers to pressure drop caused by gravitational, frictional, and accelerational effects.

The gravitational pressure drop is the dominant one, and friction accounts for only about **2-5 %** of the total pressure drop in the well. So the frictional pressure drop will also be neglected here to simplify the approach.

If there are water and vapor in equilibrium at the separator, the well head parameters can be calculated in the terms of the separator water-vapor parameters. The **mass** and energy balance equations can written as

$$m_{l,hd} + m_{v,hd} = m_{l,sp} + m_{v,sp} \qquad .....4$$

$$\tfrac{1}{2}m_{l,hd}u^2_{l,hd} + \tfrac{1}{2}m_{v,hd}u^2_{v,hd} + m_{l,hd}H_{l,hd} + m_{v,hd}H_{v,hd} = \tfrac{1}{2}m_{l,sp}u^2_{l,sp} + \tfrac{1}{2}m_{v,sp}u^2_{v,sp} + m_{l,sp}H_{l,sp} + m_{v,sp}H_{v,sp} \qquad .....5$$

The void fraction which is the fraction of cross section area occupied by vapor phase is defined as

$$\alpha_{hd} = \frac{V_{v,hd}m_{v,hd}}{V_{v,hd}m_{v,hd} + V_{l,hd}m_{l,hd}} \qquad .....6$$

The mass flow rates for vapor and liquid phase at the well head can be expressed as

$$m_{v,hd} = \frac{V_{v,hd}\alpha_{hd}A_{hd}}{V_{v,hd}} \qquad .....7$$

$$m_{l,hd} = \frac{V_{l,hd}(1-\alpha_{hd})A_{hd}}{V_{l,hd}} \qquad .....8$$

There are five equations **(4** to **8)** to calculate the five **unknown quantities such as** $m_{l,hd}$, $m_{v,hd}$, α_{hd}, $u_{l,hd}$ **and** $u_{v,hd}$ The procedure *can* be repeated dividing the well height in small segments, **until** the liquid saturation conditions are reached. After **this** point, the pressure of the liquid increases and one **has** to use compress-water ***steam*** table data. One has to include the potential energy in the energy conservation equation in these calculations in the well. The equation for concentration calculations is the Same **as** discussed in earlier method with slight modification. The vapor fraction must be calculated **as**

$$y_{sp} = \frac{m_{v,sp}}{m_{v,sp} + m_{l,sp}} \qquad .....9$$

If there is only superheated ***steam*** at the separator, the well head parameters **can** be calculated using steam **as** ideal *gas* and reversible adiabatic process.

$$\tfrac{1}{2}m_{v,hd}u^2_{v,hd} + m_{v,hd}H_{v,hd} = \tfrac{1}{2}m_{v,sp}u^2_{v,sp} + m_{v,sp}H_{v,sp} + \frac{RT_{sp}}{\gamma-1}\left[1-\left(\frac{P_{hd}}{P_{sp}}\right)^{\frac{\gamma-1}{\gamma}}\right] \qquad .....10$$

where R and y are the **gas** constant and the ratio of heat capacities, respectively (Smith and Ness, **1975).**

The value of y for vapor is 1.3. The temperature and pressure relation can be expressed as

$$\frac{T_{sp}}{T_{hd}} = \left(\frac{P_{sp}}{P_{hd}}\right)^{(\gamma-1)/\gamma} \qquad .....11$$

The calculation must be repeated **as** discussed above dividing the well height in small segments until vapor saturation is reached. After this point the two phase flow concepts must be used.

3. RESERVIOR PARAMETERS CALCULATION FOR CP-M19A WELL

Table 1 shows a data set for geochemical analysis of a geothermal well **(M-19A)** from Cerro Prieto. The chemical analysis data are taken from Henley et al **(1984)** and the production and well depth data are fiom Aragon **(1985).** The reservoir enthalpy, calculated fiom the flow rate of water and vapor, and the pressure at the separator, is somewhat higher than the reported one.

We consider here a simple case of two phase (vapor and liquid) production. It could be possible to have only vapor phase at the well head, while there may be liquid and/or vapor at the bottom of the well. If there is a liquid phase at the bottom and we are getting only vapor at the well head, then the question arises— where are the dissolved constituents? Are they deposited on the wall of well or do they return to the reservoir? **This** article is not intended to answer such question.

The chemical concentration of total dissolved species at the bottom of the well calculated using different approachs are shown in Table 2. According to Henley et **al(1994)** the reservoir fluid could be characterized as

Normal enthalpy fluid	$t_{NaKCa} > t_{quartz}$ $H_{TD} \cong H_{NaKCa} > H_{quartz}$
High enthalpy fluid	$t_{NaKCa} >> t_{quartz}$ $H_{TD} > H_{NaKCa} > H_{quartz}$
Low enthalpy fluid	$t_{quartz} < t_{NaKCa}$ $H_{TD} \cong H_{quartz} < H_{NaKCa}$

They have pointed out that the high enthalpy fluid is a result of reservoir boiling with preferential ***steam*** flow to the well, whereas low enthalpy discharge may occur where multiple feed zones intersect the well or where exploitation **has** led to inflow of relative cold water.

The reservoir temperatures calculated by applying quartz and Na-K-Ca geothermometers are **240** and **235°C**, respectively; whereas the liquid temerature to enthalpy is **273 "C.** It is somewhat higher than that calculated with chemical geothermometers, but the quartz and Na-K-Ca temperatures are in good

Table 1: **A data** set for the geochemical analysis of a geothermal well **from** Cerro Prieto **(M-19A)**. The **data** are taken **from** Henley et **al (1994)** and Aragon **(1985).**

Well No :	....	Well head pressure:	35 bar (absolute)
Well Height:	1425 m	Well separator pressure:	7.55 bar (absolute)
Well Diameter:	30 *cm*	Atmospheric pressure:	1 bar (absolute)
		Vapor production (at **sep.**):	63.2 ton/hr
Date of sampling :	....	Water production (at wairbox):	97.8 ton/hr
		Reservoir Enthalpy :	1203 J/gm

Chemical Analysis of separated water at the weirbox:

Na^+	7370 ppm	Cl^-	13800 ppm
K^+:	1660 ppm	SO_4^{2-}	18 ppm
Ca^{2+} :	438 ppm	$HCO_3^-{}_T$:	52 ppm
Mg^{2+} :	0.4 ppm	SiO_2	808 ppm
Li^+:	200 ppm	pH (at 20°C):	7.4
B:	14.4 ppm		
As	5 ppm		

Chemical analysis of vapor at the separator:

Total gas in steam (x_g): 5.88 mmole/ mole steam

CO_2:	822 mmole/mole total gases
H_2S:	79.1 mmole/mole total gases
CH_4:	39.8 mmole/mole total gases
H_2:	28.6 mmoldmole total gases
$N_2(+Ar)$:	5.1 mmole/mole total gases
NH3 :	23.1 mmole/mole total gases

Table 2: The deep reservoir physical-chemical parameters of the fluid calculated with different appraoches

Parameter	Henley et al (1984)	Giggenbach (1980)	Two phase flow approach@		
			1	2	3
Temp (°C)	240 °C	240 °C	248 °C	260 °C	276 °C
Press. (bar abs)	33.4 bar Abs.	33.4 bar abs.	38.7 bar abs.	46.9 barabs.	60.1 bar abs.
Vapor Fraction	0%	3.36 %	22.4%	20.3%	17.1%
		Liquid phase			
Na^+	5605 ppm	5800 ppm	6077 ppm	5921 ppm	5692 ppm
K^+:	1264 ppm	1306 ppm	1369 ppm	1334 ppm	1282 ppm
Ca^{2+} :	333 ppm	345 ppm	361 ppm	352 ppm	338 ppm
Mg^{2+} :	0.3 ppm	0.3 ppm	0.3 ppm	0.3 ppm	0.3 ppm
Li^+:	152 ppm	157 ppm	164 ppm	161 ppm	154 ppm
B:	10.9 ppm	11.3 ppm	11.9 ppm	11.6 ppm	11.1 ppm
As	3.8 ppm	3.9 ppm	4.1 ppm	4.0 ppm	3.9 ppm
Cl^-	10495 ppm	10860 ppm	11379 ppm	11089 ppm	10658 ppm
SO_4^{2-}	13.7 ppm	14.2 ppm	14.8 ppm	14.5 ppm	13.9 ppm
$HCO_3^-{}_T$:	39 ppm	40.9 ppm	42.9 ppm	41.8 ppm	40.2 ppm
SiO_2	614 ppm	636 ppm	666 ppm	649 ppm	624 ppm
CO_2^*	116.19	20.79	6.71	9.84	16.67
H_2S	11.28	4.25	1.66	2.31	3.61
CH_4	5.69	0.31	0.11	0.15	0.29
H_2	4.03	0.16	0.09	0.08	0.15
$N_2(+Ar)$	0.72	0.02	0.05	0.01	0.02
NH_3	4.49	3.94	3.18	3.47	3.90
		Vapor phase			
CO_2^{ξ}		28.6	7.55	8.19	9.37
H_2S		2.1	0.69	0.74	0.81
CH_4		1.6	0.37	0.41	0.48
H_2		1.1	0.27	0.29	0.35
$N_2(+Ar)$		0.2	0.05	0.05	0.06
NH_3		0.2	0.15	0.16	0.16

* **gas** concentration in liquid phase are reported in 10^{-5} mol gas/ mol water.

ξ **gas** concentration in vapor phase are reported in mol **gas** / mol steam.

® the concentrations are calculated with considering well height of 500, 1425 and 3000 m for the case of 1, 2 and 3, respectively agreement. So, it *can* be considered that there is no loss or gain of enthalpy and total discharge compositions are the deep reservoir concentration.

The second approach, mostly used in geothermal fluid geochemistry literature, is based on the important work on geothermal gas equilibria of Giggenbach (1980). The approach is based on the equilibrium of two reactions: Fischer-Tropsch reaction and/or dissociation of ammonia into N_2 and H_2. Because of the large differences in the solubilities of the gases considered, a small variation in the amount of deep vapor added to or lost fiom a geothermal discharge *can* lead to large variation in the relative gas contents. Applying **this** method, the chemical composition of reservoir fluid is calculated (Table 2). It shows excess ***steam*** of 3.36% in the reservoir.

The reservoir fluid compositions calculated with the two phase flow method are also shown in the Table 2. If we change the height of the well, we will get different composition of the reservoir fluid. It has been observed different proportions of steam and separated water in the separator result from changing the orifice at well head (Aragon, 1996). This indicates that the enthalpy measured **from** the production data depends on the well operation conditions.

3. CONCLUSIONS:

The two phase flow approach to calculate reservoir parameters is based on the valid theoretical concepts: ***steady state*** two ***phase flow*** and ***total energy conservation.*** It uses only parameters which *can* be measured **correctly** at the well head and separator. Whether the fluid entering at the bottom of well is compressed liquid, mixture of vapor and water or superheated steam, *can* be determined without using any empirical relations. The important contribution of **this** study is that it provides temperature and pressure with chemical compositions in the reservoir, are the parameters of fundamental importance in modeling geochemical processes in a geothermal reservoir. The approach *can* be improved by incorporating the friction among vapor and liquid phases and the walls of the well, and the effect of dissolved species on the properties of vapor and liquid phases. It is necessary to measure pressure and temperature independently at the well head and separator to determine the geochemistry of geothermal system.

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Nomenclatures

The symbol **stands** for

A – Area of cross section
B – Gas distribution coefficient
H – Specific enthalpy
m – Flow rate
P – Pressure
T – Temperature
u – Flow velocity
V – Specific volume
y – Fraction of vapor
a – Void fraction
y – Specific heat ratio for superheated ***steam***

The subscripts have the following significance

hd – well head
1 – liquidphase
R – reservoir
sp – separator
v – vaporphase

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