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THERMODYNAMIC CLASSIFICATION OF GEOTHERMAL SYSTEMS

Mahendra P. Verma

Depto. de Geotermia, Instituto de Investigaciones Electricas
Apartado Postal 1-475, Cuernavaca
Morelos 62001, Mexico

ABSTRACT

A thermodynamic approach is presented to classify geothermal reservoir as vapor or liquid dominated. According to it, the vapor dominated reservoir has specific volume of fluid (i.e. combined vapor and liquid) greater than the critical volume of water whereas the liquid dominated reservoir has lesser specific volume. Enthalpy is not a conservative entity in a geothermal system. Apart from it, the measured enthalpy depends on the pressure and temperature conditions of well head and separator. It means that the enthalpy measured at well separator is not reservoir enthalpy. It should be called as production or discharge enthalpy instead of reservoir enthalpy at the temperature and pressure conditions of well head and separator. Using these concepts and a simplified two phase flow, a method is developed to calculate the specific volume of reservoir fluid. The approach is applied in case of well M-19A of Cerro Prieto geothermal system. The Cerro Prieto reservoir under this well is vapor dominated.

INTRODUCTION

On the basis of geological characteristics and the mechanisms of heat transfer to the earth's surface, the geothermal resources can be divided in three major classes as: **i. *hydrothermal convection systems*** *ii.* ***geopressured geothermal systems and iii. hot dry rock and molten magma systems.*** The hydrothermal systems are presently in exploitation stage in many parts of the world. The hydrothermal systems are further subdivided as ***vapor dominated and liquid dominates systems*** to understand the production characteristics and geochemistry of their reservoir.

Fluid geochemistry is a valuable tool in the evaluation of energy potentials of geothermal systems. 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.

The various geothermal reservoirs have been distinguished as vapor dominated such as Larderello fields of Italy, The Geysers of California, Matsukawa, Japan which produce dry steam or superheated steam with little of no associated water (Truesdell and White, 1973). They also reviewed the existing models to explain the formation of vapor and liquid dominated reservoirs, which were based on the measured in-hole temperature and shut-in pressure. but they noticed that the in-hole temperature and shut-in pressure in other vapor dominated fields seemed to be quite different. The model proposed by White et al (1971) considers that a geothermal reservoir contains both steam and water in its natural state prior to production. These systems are formed initially from hot water systems when the heat supply is large relative to the heat transfer ability of the convecting liquid water in the system. This situation is caused primarily by low permeability of the rocks bounding the sides of the reservoir, with resulting low rates of recharge. When, due to increasing heat or decreasing permeability form self sealing, more water is boiled off than is replaced by recharge, a vapor dominated system begin to form.

There exists an extensive literature on numerical calculation of reservoir characteristics of a vapor dominated geothermal reservoir (Young, 1996 and references cited in). But the basic definition of a vapor dominated is not clearily presented, yet. One can

In this article a thermodynamic definition of a vapor dominated geothermal system is presented, which is based on the calculation of specific volume of the fluid in the geothermal reservoir. The calculation of specific volume is done by applying a simplified two phase flow approach using the laws of conservation of mass and total energy (mechanical and thermal energies). The dissolved contents of gases and salts can change the thermodynamic characteristics of geothermal fluids drastically (White et al, 1971), but here the pure water characteristics are used to demonstrate the concepts of thermodynamic classification the geothermal reservoir as vapor or liquid dominated reservoir.The approach is applied in case of well M-35 of the Cerro Prieto geothermal system which shows that the Cerro Prieto geothermal reservoir under the well M-35 is vapor dominated.

P-V-T BEHAVIOR OF GEOTHERMAL FLUID

The characteristic thermodynamic properties, such as internal energy, enthalpy and Gibbs free energy of geothermal fluids cannot be measured directly, whereas these properties are of fundamental importance in chemical thermodynamic calculations. Fortunately, for fluids in equilibrium states the properties are function of measurable parameters such as pressure, temperature, volume and dissolved constituents. In discussing the thermodynamic behavior of geothermal fluid it can be assumed the effect of dissolved constituents as very small. Here, a general behavior of the PVT relation of the fluids (i.e. pure water) is looked for the definition of vapor-liquid dominated reservoir. The most of the discussion is taken from Smith and Ness (1975) for sake of completeness. These concepts are used in the computer programming of the two phase flow method. The work of Smith and Ness (1975) could be resumed as:

*Figure 1(a) demonstrates a general PT diagram **for** a pure material. The phases liquid and gas distinction cannot always be sharply drawn because the two phases become indistinguishable at critical point. Line 2-C is the vaporization curve and separates the liquid and gas regions. If the system exists along this two phase line, it is univariant, whereas in the single phase regions it is divariant. The vaporization curve 2-C terminates at point **C.** The coordinates **of** this point are called critical pressure Pc, and critical temperature Tc. These represent the highest temperature and pressure at which the geothermal fluid can exist in vapor-liquid equilibrium.*

*Figure 1(b) shows the plot **of** pressure vs. molar or specific volume **of** isotherms which would be vertical lines in the Figure 1(a). The isotherm labeled T_1 is at temperature greater than the critical temperature T_c. The line T_2 is **for** lower temperature and consists **of** three distinct sections. The horizontal sections represent the phase change between vapor and liquid. The constant pressure at which this occurs **for** a given temperature is the vapor pressure, and is given by a point on Figure 1(a) where the isotherm crosses the vaporization curve. Points along the horizontal lines **of** Figure 1(b) represent all possible mixtures **of** vapor and liquid in equilibrium, ranging from 100 percent liquid at the left end to 100 percent vapor at the right end. The locus **of** these end points is represented by the dome-shape curve labeled **ACB,** the left half **of** which (from A to C) represents saturated liquid, and the right half **(from C** to **B)** saturated vapor. The area under the dome **ACB** is the two-phase region, while the areas to the left and right are the liquid and gas regions, respectively.*

*The significance **of** the critical point becomes evident from a consideration of the changes that occur when a pure substance is heated in a sealed upright tube **of** constant volume (Figure 1(c)). If the tube is only partially filled with liquid (the remainder being vapor in equilibrium with the liquid), heating at first causes changes which are described by the vapor-pressure curve (solid line). If the meniscus separating the two phases is initially near the bottom **of** the tube (Figure 1(c)iii), the liquid vaporizes, and the meniscus recedes to the bottom **of** the tube and disappears as the last drop **of** liquid vaporizes. For example in Figure 1(a), one such path is from (J,L,K) to N; it then follows the constant-volume line V upon further heating. If the meniscus is originally near the top **of** the tube (Figure 1(c)i), the liquid expands upon heating until it completely fills the tube, One such process is represented by the path from (J,L,K) to P; it then follows the constant- volume line V' with continued heating. The two path are also shown by the dashed lines in Figure 1(b), the first passing through points K and **N,** and the second, through J and P.*

*Between these there is an amount **of** liquid that can be added to the tube (Figure 1(c)ii) initially such that the path **of** the heating process coincides with the vapor-pressure curve **of** Figure 1(a) all the way to its end at the critical point C. Further heating produces changes represented in Figure 1(a) by a path along V_c, the constant-volume line corresponding to the critical volume **of** the fluid.*

It is clear from the above discussion that the geothermal system could be classified as vapor and liquid dominated which have specific volume of the fluid in the reservoir less or greater than the critical volume, respectively. If the specific volume of the reservoir fluid, combined liquid and vapor is less than the critical volume, all the fluid will convert in vapor only as it get heated with country rocks in the reservoir and vice versa. But both the types of ›othermal reservoir could produce only vapor phase the well head depending upon the pressure and mperature conditions of the production and in the ›servoir. And it is not correct to define the type of ›othermal reservoir with the characteristics of ›othermal fluid at well head. Thus it is necessary to ılculate the deep reservoir fluid specific volume form ıe fluid characteristics at well head to classify the ›othermal system.

is very commonly used to measure the reservoir ıthalpy from the production data of vapor and liquid . the well separator pressure. If the orifice of the well ead (i.e. well head pressure) is changed, the roduction of vapor and liquid at the same separator onditions will be different. Thus the enthalpy will lso be different. In other words, with changing the ʼell head parameters one can change the reservoir nthalpy, which does not sound correct. So, it is orrect to call the *production enthalpy,* instead of ›servoir enthalpy at the well head and the separator ›mperature and pressure conditions.

ι comparative study of different approaches on the alculation of deep reservoir fluid parameter is resented by Verma (1996). The approach which is ıore commonly used in the literature is based on the onservation of mass and thermal energy (Enthalpy). ʼhe first calculations are made assuming a single ʼhase (liquid) in the reservoir which is not always the ase. To obtain the fraction of steam at the feeding one of a geothermal well Henley et al (1984) used he measured and chemical geothermometers (SiO_2 nd NaKCa) derived enthalpies to calculate excess nthalpy and excess vapor. According to them the eservoir 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	$t_{quartz} < t_{NaKCa}$ $H_{TD} \cong H_{quartz} < H_{NaKCa}$

ʼhey have pointed out that the high enthalpy fluid is a ʼesult of reservoir boiling with preferential steam flow o the well, whereas low enthalpy discharge may occur where multiple feed zones intersect the well or where ›xploitation has led to inflow of relative cold water. ʼhey used the terms vapor “excess steam” for

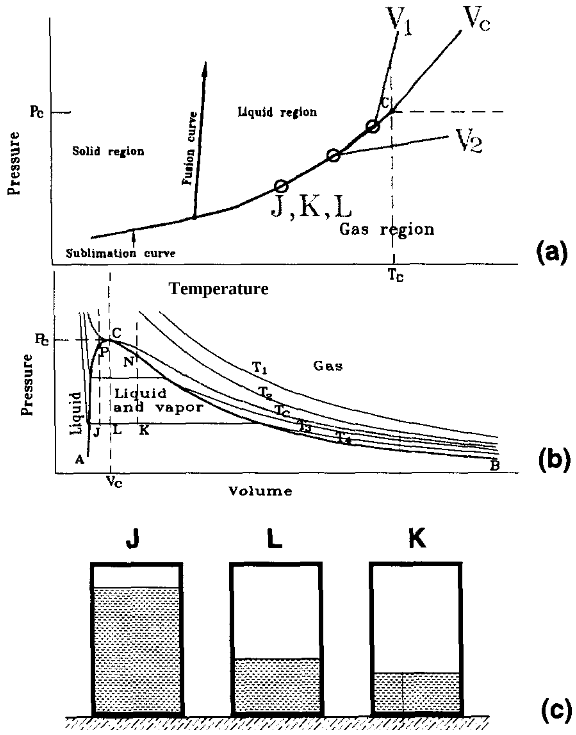

Fig. I. P-V-T diagramfor a geotehrmalfluid without considering the efects of dissolved constituents. (a)P-T diagram (b)P-V diagram and (c) a hypothetical case of water-vapor ratio in a geothermal system is shown to distinguis the three possible options: i. liquid dominated, ii. critical condition and iii. vapor dominated reservoir.

the fraction of steam calculates with this methods and the “excess enthalpy” to the enthalpy associated with this steam in the reservoir.

The approach of Giggenbach to calculate excess steam is based on the distribution of gaseous components, methane, carbon dioxide, hydrogen and vapor. This approach is mostly used in geothermal fluid geochemistry literature. It is an outcome of the work on geothermal gas equilibria (Giggenbach, 1980). The equilibrium constants of two reactions: *Fischer-Tropsch reaction and/or dissociation of ammonia into N_2 and H_2* are used. 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 from a geothermal discharge can lead to large variation in the relative gas contents. Nieva et al (1984) modified this approach for the case of high concentration of volatile species other than steam in the vapor phase.

The excess word in defining excess steam and excess enthalpy seems to be misleading. As in a geothermal reservoir there could be different proportion of vapor

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.

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 the production characteristics 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 (Verma, 1996). 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 a few percentage 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

$$m_{l,hd} + m_{v,hd} = m_{l,sp} + m_{v,sp} \qquad \text{..... 1}$$

$$\tfrac{1}{2} m_{l,hd} u_{l,hd}^2 + \tfrac{1}{2} m_{v,hd} u_{v,hd}^2 + m_{l,hd} H_{l,hd} + m_{v,hd} H_{v,hd}$$
$$= \tfrac{1}{2} m_{l,sp} u_{l,sp}^2 + \tfrac{1}{2} m_{v,sp} u_{v,sp}^2 + m_{l,sp} H_{l,sp} + m_{v,sp} H_{v,sp} \qquad \text{.... 2}$$

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

$$\alpha_{hd} = \frac{V_{v,hd} m_{v,hd}}{V_{v,hd} m_{v,hd} + V_{l,hd} m_{l,hd}} \qquad \text{..... 3}$$

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

$$m_{v,hd} = \frac{u_{v,hd} \alpha_{hd} A_{hd}}{V_{v,hd}} \qquad 4$$

$$m_{l,hd} = \frac{u_{l,hd} (1 - \alpha_{hd}) A_{hd}}{V_{l,hd}} \qquad \text{..... 5}$$

There are five equations 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 (2) 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

$$y_{sp} = \frac{m_{v,sp}}{m_{v,sp} + m_{l,sp}} \qquad \text{.....6}$$

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.

(1

Here it is supposed that the vapor and liquid don't

RESERVOIR PARAMETERS CALCULATION FOR CP-M19A WELL

the two approaches. It takes input data for liquid phase as the chemical composition of separated water at atmospheric pressure in weirbox and for vapor phase the chemical composition of gases on dry basis, gas fraction in vapor conduit in the separator and well head and separator pressures. Apart from it, the construct data of well and the conduits of vapor and liquid are also required. The program is composed on various subroutines and functions. Some of the important subroutines are the followings: i. ***StmTbl***: It provides the saturated steam table from 0°C to the critical point of water (375.15°C). ii. ***FracCoeff:*** This subroutine computes the fractionation coefficients of the gases, CO_2, H_2S, NH_3, CH_4, N_2 and H_2 at a specified temperature. iii. ***WellHead:*** This subroutine calculates the vapor and liquid phase compositions at well head using input data and conservation of mass and total energy (thermal and mechanical energy). iv. ***WellPos:*** Once the fluid compositions at well head are known. The subroutine WellPos starts calculating the compositions in the well with dividing it in small segments (say 10 m length) in an iterative way till reaching the bottom of the well. The details of the computer program are presented elsewhere (Verma, 1997).

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 from Aragon (1986). The reservoir enthalpy, calculated from the flow rate of water and vapor, and the pressure at the separator, is somewhat higher than the reported one.

The reservoir temperatures calculated by applying quartz and Na-K-Ca geothermometers are 285 and 281°C, respectively; whereas the liquid temperature 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 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 chemical compositions of reservoir fluid calculated using this approach are given in the Table 2. Applying Giggenbach method, there shows an excess steam of 33.6% in the reservoir and the chemical compositions of reservoir fluid calculated using this approach are also given in the Table 2.

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. It means that the solid phase (dissolved constituents) are deposited on the wall of well or returned back to the reservoir.

The reservoir fluid compositions calculated with the two phase flow method are also shown in the Table **2.** If we change the depth of the well, we will get different composition of the reservoir fluid. It is similar to say that one can get different proportions of steam and separated water in the separator result from changing the orifice at well head. This has been observed almost in all the geothermal fields. Recently, it examined experimentally in the laboratory by Okabe (1996).

The specific volumes calculated for different depths of the well are shown in the Table 2, which are 12.6, 9.6 and 6.6 c.c./g for the well depths of 500, 1450 and 3000 m, respectively. The critical volume of water is 3.16 c.c./g. It means that the well CP-M19A is producing from a vapor dominated reservoir.

CONCLUSIONS

The reservoir which has specific volume of the fluid less than the critical specific volume is vapor dominated, whereas the reservoir having fluid specific volume greater than critical specific volume is liquid dominated. 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, a 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; these parameters are 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, the effect of dissolved species on the properties of vapor and liquid hases and compressed liquid and superheated steam able. The fractional pressure is also very important as ıe diameter of well has very dominative role in overning the fluid flow conditions. The Cerro Prieto eservoir around the well M-19A is vapor dominated ccording to this thermodynamic classification.

lomenclatures

'he 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

The subscripts have the following significance

- hd – wellhead
- l – liquid phase
- R – reservoir
- sp – separator
- v – vapor phase

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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 (1986).

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
CH4:	39.8 mmole/mole total gases
H_2:	28.6 mmole/mole total gases
N_2(+Ar):	5.1 mmole/mole total gases
NH_3:	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]		
			1	2	3
Temperature (°C)	281	281	248	260	276
Pressure (bar Abs.)	65.1	65.1	38.7	46.9	60.1
Vapor Fraction	0	0.015	0.224	0.203	0.171
Specific Volume (c.c./g)[2]			12.6	9.6	6.6
Liquid phase (concentrations are in ppm or 10^{-5} molar gas/mole water)					
Na^+	5605	5692	6077	5921	5692
K^+	1263	1282	1369	1334	1282
Ca^{2+}	333	338	361	352	338
Mg^{2+}	0.3	0.3	0.3	0.3	0.3
Li^+	152	154	164	161	154
B	10.9	11.1	11.9	11.6	11.1
As	3.8	3.9	4.1	4.0	3.9
Cl^-	10495	10658	11379	11089	10658
SO_4^{2-}	13.7	13.9	14.8	14.5	13.9
$HCO_3^-{}_T$	39	40.1	42.9	41.8	40.2
SiO_2	614	624	666	649	624
CO_2	116.19	66.90	6.71	9.84	16.67
H_2S	11.28	8.75	1.66	2.31	3.61
CH_4	5.69	1.82	0.11	0.15	0.29
H_2	4.03	1.02	0.09	0.08	0.15
N_2(+Ar)	0.72	0.01	0.05	0.01	0.02
NH_3	4.49	4.30	3.18	3.47	3.90
Vapor phase (concentrations are in mmole gas/mole steam)					
CO_2		32.82	7.55	8.19	9.37
H_2S		1.74	0.69	0.74	0.81
CH_4		2.49	0.37	0.41	0.48
H_2		1.97	0.27	0.29	0.35
N_2(+Ar)		0.02	0.05	0.05	0.06
NH_3		0.17	0.15	0.16	0.16

[1] the concenttations are calculated utilizing well depths of 500, 1425 and 3000 m for cases 1, 2 and 3.
[2] The specific volume of the fluid in the reservoir including both vapor and liquid.