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VAPOR-DOMINATED FIELDS: FLUID RESERVES AND GEOTHERMOMETRY

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ABSTRACT

A vapor-dominated reservoir is modelled as a uniform porous medium containing immobile water and mobile steam. Changes in concentrations of different gas species are used to determine the porosity and liquid saturation of the reservoir. The "grid" method provides an incomplete analysis of this type of reservoir, either for water content or reservoir temperature.

It is conjectured that the reservoirs of Kamojang and Darajat in Indonesia are significantly wetter than The Geysers, and consequently have greater fluid reserves per cubic kilometre.

INTRODUCTION

A vapor-dominated reservoir contains steam as the principal or only mobile phase, and liquid water immobile or slightly mobile in the reservoir matrix or blocks of a fractured reservoir. Wells discharge dry or slightly wet saturated steam, and after exploitation superheated steam. The reserves of the reservoir are the liquid in the pores: this is where the reservoir's mass is stored. Usually the amount of liquid is insufficient to extract all the stored heat in the rock, so the amount of liquid is the factor determining the amount of steam that can be produced.

This amount of liquid is a physical quantity very difficult to determine. To measure the amount of water requires some measurable physical quantity that changes with the saturation. Gas contents appear the logical candidate, since gas contents of both phases must change as water boils. There are many complicating chemical factors, however the presence of the physical mechanism, boiling and exsolution, requires there to be some effect of the amount of liquid.

There have been two routes taken to so analyse gas contents, by Grant (1979) using the variation in gas ratios to estimate saturation, and by Arnórsson, and D'Amore and colleagues to estimate reservoir temperature and "y".

The reservoirs of Kamojang and Darajat in Indonesia are adjacent vapor-dominated fields with very similar thermodynamic conditions, hosted in fractured volcanic rocks. Wells produce saturated steam, often with up to 5-15% of water initially, from reservoir temperatures of 240-245°C (Whittome & Salveson 1990, Grant 1979, Sudarman et al. 1995). Kamojang has been producing since 1979 with little change in reservoir temperature or pressure. Darajat began production in 1994.

FLOW TO THE WELL (TRANSIENT FLOW MODEL)

Grant (1979) modelled transient flow to a well producing steam from a reservoir of steam and immobile water. There is assumed to be an initial state in which the phases are in physical equilibrium. Water boils from the trapped liquid along the path to the well, and there is equilibrium at all times between the two phases. Thus there is continuing transfer of heat from rock to fluid, and transfer of mass, both steam and gas, from liquid to vapor phase.

The method is based upon standard models for transient flow in the reservoir and equilibrium distribution of gases between liquid and vapor phases. The analysis prescribes the transient change in gas concentration after well opening, the variation of stable gas content with flow rate and the relation between changes in gas ratios. Grant (1979) used the last for analysis of field data.

The stable gas content at the wellhead is related to reservoir concentration by:

$$\ln(x_{WH}/x_R) = -C(\zeta)$$

$$\zeta = \frac{W}{4\pi kh}\frac{\mu c_t}{\gamma} = \frac{W}{4\pi kh}\frac{\mu\phi c_t}{\phi\gamma}$$

$$\gamma = (1-S)\rho_s + S\rho_w/B$$

$$C(\zeta) = \int_0^\infty \frac{\zeta e^{-x}dx}{x+\zeta e^{-x}}$$

Figure 1 shows calculated results for a model well.

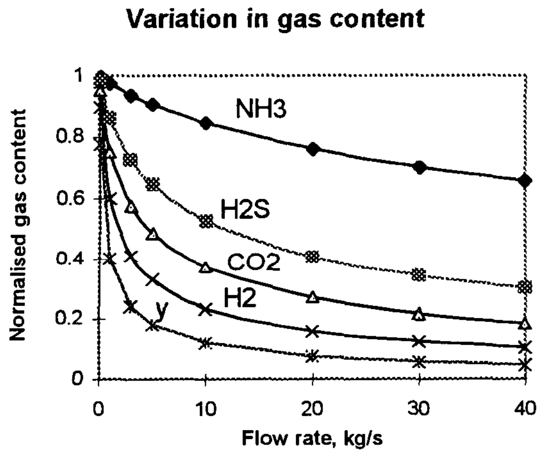

Fig. 1. Variation of gas content of steam with flow rate for model well, showing dependence on differences in gas solubility.

Different gases behave differently, depending on their different solubilities, as represented by the distribution coefficient *B*. ϕc_t is a function of temperature for two-phase conditions, so the parameter group $\phi\gamma$ is found from any analysis.

The example model well calculations, are based upon a well with *kh*=13dm, ϕ = 0.1, saturation of 0.95, and temperature of 245°C. *y* is the fraction of the steam in the discharge deriving from reservoir steam. It is computed as the concentration of a "gas" which has concentration unity in reservoir steam and zero in reservoir water, ie zero solubility. The contrast between the different gases would be less at lower saturations, and all would be identical at zero saturation, when there is no boiling. Note that *y* depends on flow rate, and declines rapidly with increasing flow rate. It is not a property of the reservoir alone but is dependent on the control of the well.

D'Amore and Truesdell (1995) have observed that "saturation" experimentally increases with increasing flow rate in data from The Geysers and Larderello. (ie, y decreases). For a group of wells of varying *kh*, under similar production conditions, stable flow rate increases with *kh*, but less than linearly due to wellbore resistance being more important at high flow. Thus the high flow wells are wells of ***low*** values of *W/kh*, and this observation reflects the effect of the physics of flow to the well, *not reservoir liquid saturation.*

In practice samples taken under normal operation will not span a wide range of values of *W/kh*. Specific tests and measurements are needed.

CHEMICAL EQUILIBRIA IN THE RESERVOIR, AND "y"

Methods of D'Amore and Arnórsson

There are two distinct schools of geochemical thought to the estimation of "y" from geothermal gas data, represented by Arnórsson on the one hand and D'Amore & colleagues on the other. Summaries of the respective positions can be found in WGC papers (Arnórsson 1995; D'Amore & Truesdell 1995).

D'Amore's ("grid") method relies on assumed equilibria between *gas* species, in the gas phase. The method has been extensively applied to vapor-dominated reservoirs yielding interpretations that appear acceptable. However the attempts to apply it to liquid-dominated reservoirs do not seem consistently successful, and yield values of y that are clearly unphysically large, as has been repeatedly pointed out by Arnórsson.

Arnórsson's method relies on *gas-mineral* equilibria, and has been validated on liquid-dominated reservoirs where it appears to give acceptable results. It does not appear to have been used significantly in vapor-dominated fields.

These reviews indicate that Arnórsson's method has not been shown valid for vapor-dominated systems, and that D'Amore & Truesdell's has not been validated for liquid-dominated systems.

Based upon its extensive use, yielding results apparently physically acceptable, it appears that the grid method is valid at least in part for vapor-dominated reservoirs.

The method's failure in liquid dominated systems is unexplained. However I note that with significant amounts of both phases moving (or primarily liquid), there are more physical processes for heat and mass transfer present than in a vapor system. Further, the grid method depends on gas equilibria and hence may fail when vapor occupies only a very small fraction of the reservoir volume, or none at all (the gases are all dissolved). Likewise Arnórsson's gas-mineral equilibria are empirically developed on liquid dominated reservoirs and so may reflect equilibria with dissolved species, and not be valid when the fluid is in vapor phase. In either case the methods are empirical and based upon calibration against field data, which means that there may be some degree of empirical compensation within the calibrations for the theoretical differences

Assumed physical and chemical processes

There are two processes involved in these chemical methods.

The first is a chemical reaction in which species in the fluid react with each other, or with the rock. This reaction is assumed to reach equilibrium at some temperature. D'Amore regards this equilibration temperature as an unknown to be found - the method is used as a geothermometer and there is the possibility that the reaction is sufficiently slow that the equilibration occurred at greater depth and temperature. Arnórsson expects the equilibration temperature to be the reservoir temperature, and so implicitly restricts theory to reactions fast enough to reflect local equilibria.

The second process is the physical transport of fluid to the well. D'Amore assumes a specific process: The fluid in the reservoir is a faction y of vapor, and $1-y$ of liquid. They are in physical equilibrium, controlled by the distribution coefficient for the temperature.

The fluid flows to the well, the liquid being vaporised to steam. There is no further chemical re-equilibration nor any exchange of fluid particularly gas with the fluid stored in the reservoir.

The distribution of gas between vapor and liquid phases is controlled by the fractionation temperature, the temperature of the reservoir from which the fluid is withdrawn. D'Amore assumes this is the same as the equilibration temperature.

What is "*y*"?

As defined in all the geochemical approaches, y is the mass fraction of a discharge that was vapor in the reservoir. It is thus the mass fraction of the vapor phase in the flowing reservoir fluid, distant from the wellbore.

It is not the vapor saturation (by mass), which is the fraction of vapor stored in the reservoir. Nor can saturation be computed from y.

This conclusion was reached by D'Amore & Pruess (1986), but the identification with vapor saturation is made by D'Amore & Truesdell (1995), and appears to be implicit in many papers using these geochemical methods. There has been confusion between the flowing mass fraction of reservoir steam, and the in-situ mass fraction of steam.

And indeed we can see from simple physical considerations that it is impossible to determine reservoir saturation from *any* single chemical sample, no matter how many species are analysed.

The reservoir contains both steam and water. Chemical species equilibrate in both phases, and possibly solid. The equilibria obey mass-action laws *but do not* depend on the relative amounts of steam and water present; only on, eg. the partial pressures of the gases. Fluid is withdrawn, a mixture of reservoir steam and water, in some ratio. This ratio is not directly related to the relative amounts in the reservoir, and the composition of each phase is not affected by the amount of each phase in the reservoir. Chemical analyses of the discharge can, hypothetically, reconstruct the initial equilibrium state, the chemical species in each reservoir phase and the proportions of each phase that contribute to the discharge. *But there is no chemical parameter in the discharge that reflects the steam-water ratio in the reservoir. These chemical measurements can only determine variables like y, properties of the* ***discharge***. The only connection is that the steam saturation in the reservoir, via the relative permeabilities, affects y, or discharge enthalpy if both phases are mobile.

Combining the chemical theory with a model of the physical flow to the well may give information on saturation, because the physical model adds a prescription for the phase changes occurring in the flow to the well.

Methods using changes in gas content

Grant (1979) used *changes* in gas contents, and the correlation between them, to determine saturation.

Similar reasoning can be applied to the changes with time as the reservoir depletes. The crucial component of these methods is that there is some change in the gas content as the reservoir pressure & temperature changes. With the local or general depletion of the reservoir, mass is transferred from liquid to vapor phase. The rate at which concentrations change depends directly on the relative proportions of liquid and vapor, so this physical process is dependent, directly, on the reservoir liquid saturation.

McCartney & Lanyon (1989) provide a useful method for the correlation of data of multiple gas observations. They fit the observed data to a mixing line between two fluids, one having the composition of vapour and the other of (vaporised) liquid in equilibrium with the vapour. The two end-member fluids are assumed to represent reservoir vapor and liquid phases. They assume appropriate equilibrium fractionation between the two phases but make no assumption about chemical equilibria between gas species.

Anomalous gas contents have been observed. In particular McCartney & Haizlip (1989) deduce anomalies in hydrogen concentration at The Geysers, and Pruess et al (1985) show that the total carbon dioxide discharge from Larderello could not have been stored in fluid phase. For these two cases then models assuming equilibria between fluid phases only will not work.

Changes with time

The model used here assumes that the principal physical mechanism involved in changes in gas content is boiling of reservoir water, and consequent dilution of reservoir steam. It inevitably follows that gas contents will decline with cumulative discharge.

The experience in Larderello and The Geysers is that in the long term, gas contents have been maintained. This is explained in two ways. In Larderello, CO_2 has been evolved from reservoir rock. The cumulative gas discharge is too great to have been stored in any fluid phase. In both fields, there has been imputed significant flow of gassier fluids from high gas regions, towards the producing areas which were generally regions of low gas content initially. This gassier steam is assumed to come from peripheral regions where there has been condensation, from deep fluids, and from unknown third sources.

Darajat and Kamojang, *in their present state,* differ from both these fields in being wet. Boiling of water, near the well, is clearly the dominant physical mechanism; while transport of steam large distances either laterally or vertically does not appear important - although it could become so when the fields have been longer exploited.

RELATIONSHIP BETWEEN GRANT AND "GRID" THEORIES

Grid theory

As summarised by D'Amore & Truesdell (1995), D'Amore's theory can be summarised by the equilibrium reactions:

$$CH_4 + 2\,H_2O = 4\,H_2 + CO_2$$

$$H_2 + (3/2)\,FeS_2 + 2\,H_20 = 3\,H_2S + (1/2)\,Fe_3O_4$$

These equilibrium reactions give:

$$4\log(H_2/H_2O) - \log(CH_4/CO_2) = K_1$$

where $K_1 = -15.35 - 3952.8/T + 4.635 \log T$ is the log of the equilibrium constant. A similar expression applies for the second reaction:

$$3\log(H_2S/H_2O) - \log(H_2/H_2O) = K_2$$

Where $K_2 = 6.231 - 6223.2/T + 0.412 \log T$.

Then applying assumptions about the physical flow of fluid from distance in the reservoir to the wellhead prescribes the changes in gas content.

The fluid derives from a fraction y of reservoir steam, and $1\text{-}y$ of reservoir liquid, in equilibrium. The two are mixed and vaporised without any further addition of fluid, and flow to the well. Then the concentration of any gas at reservoir conditions is related to wellhead conditions by:

$$x_{WH} = [y + (1-y)/B]\, x_R$$

where B is the vapor-liquid gas distribution coefficient. If we then use wellhead concentrations:

$$4\log(H_2/H_2O) - \log(CH_4/CO_2) = FT$$
$$= K_1 + f_1$$
$$f_1 = 4\log[y+(1-y)/B(H_2)] + \log[y+(1-y)/B(CO_2)] - \log[y+(1-y)/B(CH_4)]$$

$$3\log(H_2S/H_2O) - \log(H_2/H_2O) = HSH$$
$$= K_2 + f_2$$
$$f_2 = 3\log[y+(1-y)/B(H_2S)] - \log[y+(1-y)/B(H_2)]$$

The factor f_1 contains the effect of diluting the fraction y of original reservoir steam with $(1-y)$ of vaporised liquid.

The theory of Grant (1979) differs ***only*** in providing a different prescription of the physical process of flow through the reservoir to the well. On this theory, we have for each species:

$$\ln(x_{WH}/x_R) = -C(\zeta),$$

$$\zeta = [W/4\pi kh].[\mu\phi c_t/\phi\gamma]$$

The factor $[y + (1-y)/B]$ is replaced by $\exp(-C)$.

$$f_1 = -(1/2.303)[4C(\zeta(H_2))+C(\zeta(CO_2)-C(\zeta(CH_4))]$$

$$f_2 = -(1/2.303)[3C(\zeta(H_2S))-C(\zeta(H_2))]$$

Calculation of *y*

y can be computed from Grant's model. Consider the case of a fictitious gas which has concentration unity in the reservoir steam, and is completely insoluble in liquid. Then changes in the concentration of this gas are the same as changes in y:

$$\ln(y) = -C(\zeta)$$

with $\gamma(y) = (1-S)\rho_s$

Validation of Grid model

It is possible to model the flow to the well and so compute y, and also changes in all gas contents. One could therefore start with gases in chemical equilibrium for the FT and HSH reactions, compute the changes in concentrations in flow to the well, and hence the reservoir temperatures and y values as they would be computed from D'Amore's theory.

A quick check was made using the model of figure 1, but at 240°C. Reservoir conditions are for all chemical species in equilibrium.

At a flow rate of $W/kh\phi = 10$ we have FT = -14, HSH = -9.1. On the "grid" model these imply reservoir values of T= 210°C, and $y = 0.25$. The actual value of y is 0.11, and the reservoir temperature is unchanged at 240°C. The example is very sensitive to the assumed initial conditions, particularly saturation.

We conclude that the grid theory encounters some problems if the physics of flow to the reservoir do not conform to their assumptions. In this particular case it failed to correctly model the chemical changes created by a different physical model. The assumptions may be more applicable to exploited fields like Larderello and The Geysers, where steam flows from some distance, and therefore may genuinely correspond to a model of flow from a source with no change along the way. However this model is not applicable to any little-exploited steam field, where there is clearly boiling of water all the way along the flow path to the well. Note that there is no difference in the chemistry, but only in the physical model of flow to the well.

It is a clear conclusion that the physics of flow to the well affects gas contents of discharge and the gas ratios, and can distort geothermometers. It is frequently observed that geothermometers based on gas equilibria give high reservoir temperatures. This may be an effect of the flow to the well rather than equilibration at higher temperature.

BOX MODELS

If we have a confined volume V of rock containing water and steam, and withdraw steam at rate W, and the steam is always in equilibrium with the block from which it flows, we have for the gas content of the steam:

$$V\phi \frac{d}{dt}\left[Sx_w\rho_w + (1-S)x\rho_s\right] = -xW$$

or $$\ln(x/x(0)) = -W/[V\phi\gamma]$$

If we have two gases, the logs of the two concentrations vary linearly with each other, with slope:

$$\frac{d(ln(x_1)}{d(ln(x_2))} = \frac{\gamma_2}{\gamma_1}$$

This is the same as the approximate relationship derived by Grant (1979) for transient well flow. Figure 2 compares the relationship between CO_2 and H_2S concentrations with the box model and the transient flow model.

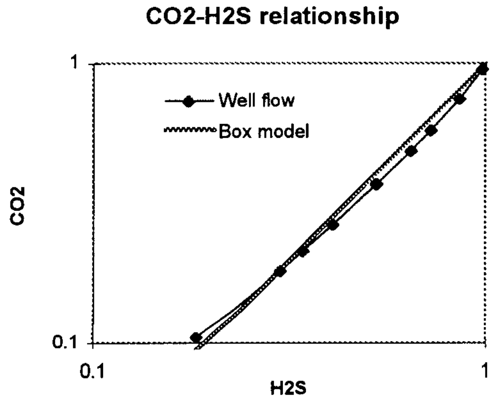

Fig. 2. Gas-gas variation according to transient well flow and box models. Log-log plot.

The heavy line represents the box model decline. In practice the transient flow model can barely be distinguished from the box model. Despite the limitations of the model of flow to the well, much the same correlation between two gases will be observed as with the very different box model. This similarity is reassuring, as it implies some robustness of inferences based on changes in gas ratios.

This box model may represent a better idealisation of the long-term depletion of a reservoir than the transient flow model.

SIMULATIONS

The theory and its application are necessarily simple. Some effects such as fractured media have been ignored completely. However these cases are quite adequate to demonstrate the strong effect on gas contents and ratios of the physical processes occurring during flow to the well.

Models of two-phase flow to wells show similar results (Sorey et al. 1980), and the strong dependence of the variation on porosity and saturation. A thorough analysis of changes in gas content in a vapor reservoir will require simulation of the flow of the steam-gas mixture to the well. Fitting enthalpy history of two-phase fields requires detail near each well: so does the gas content.

EFFECT OF ADSORPTION

Extension to the case of a reservoir with immobile adsorbed water is straightforward. In this case pressure and temperature are related through the saturation. Following the notation of Horne et al. (1995), we can summarise the thermodynamic conditions with adsorption as:

$$P = P_s(T)f(S),$$

where $f(S)$ is less than unity and approaches unity as saturation increases (as the effects of adsorption becomes negligible). In the reservoir, with steam as the only mobile phase,

$$<\rho C> \frac{\partial T}{\partial t} = \phi(\rho_w - \rho_s)(H_s - H_w)\frac{\partial S}{\partial t}$$

ie a simple linear relation between saturation and temperature. As one would physically expect, the temperature falls with the boiling of immobile water, whether or not there is an adsorption effect. Combining this with the adsorption equation means we now have a relationship between temperature and pressure, a pseudo-saturation relationship. The practical effect is that the fluid compressibility is altered through the change in dP/dT:

$$\frac{dP}{dT} = f(S)\frac{dP_s}{dT} + P_s f'(S)\frac{dS}{dT}$$

This affects pressure transients and gas contents of the discharge, through the changed parameters. But the form of the equations is unchanged, only the parameters change. In general the effect of the change is to decrease the changes in gas contents.

VARIATION OF GAS CONTENT WITH FLOW RATE: FIELD EXAMPLE

Some measurements of gas content under different conditions are available for a well in Darajat field. This well shows significant variation in total gas content. This is the only well to show such clear systematic variation in gas content. Other wells generally have few measurements, and greater scatter. The data shows a tighter grouping when plotted against flowrate than against WHP. The total gas content varies strongly with flow rate. Extrapolating to zero flow would give over 5%.

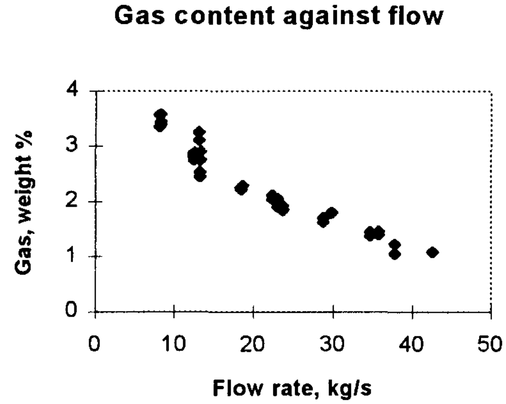

Fig. 3. Gas fraction-flowrate relationship

Figure 4 shows the mass flow of gas against total flow, and a fit, using the model of figure 1 and a reservoir temperature of 240°C. The fitted curve has parameters: $\phi\gamma = 5$ kg/m^3, $f_o = 9\%$.

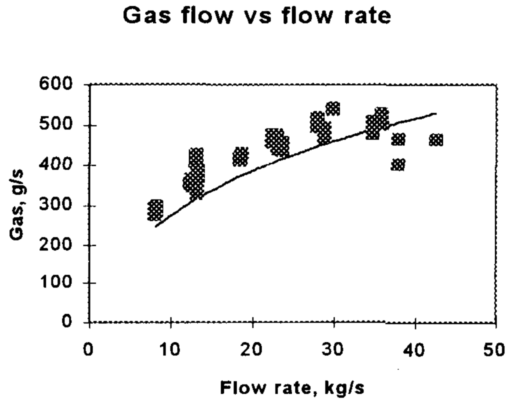

Fig. 4. Total gas flow against flowrate, and fitted model.

The value of $\phi\gamma$ implies a porosity of at least 30% - the flow must represent behaviour in fractures rather than reservoir matrix. The value of f_o, representing the concentration of gas in reservoir vapour, is significantly higher than any measured concentration. However inspection of the figures above shows clearly that any extrapolation to low flows will give high gas contents. The gas content is strongly and nonlinearly dependent on flow rate. It is common to all geochemical theories interpreting gas concentrations that they infer significantly higher reservoir gas contents, because they infer significant dilution of reservoir steam by boiled water.

A CONJECTURE ON RESERVOIR LIQUID CONTENT

It is conjectured that the Indonesian fields, Kamojang and Darajat, are wetter than The Geysers, ie contain more liquid per unit reservoir volume. This conjecture is based upon comparison of available information but there is insufficient evidence to validate it.

First impressions of the Indonesian fields are certainly that they are very wet. Wells may discharge up to 15% water, and thermodynamic conditions are unquestionably saturated and have remained so. This appears to contrast to The Geysers where superheat appears earlier.

Grant (1979) and this analysis of Darajat require high porosities. In contrast to greywacke at The Geysers, the Indonesian fields are hosted in volcanics of higher porosity than greywacke.

We therefore conjecture that the Indonesian fields have higher porosity, and consequently higher water content in terms of water per unit reservoir volume (ϕS). The practical implication is a higher fluid reserve per unit volume. And planned developments at Kamojang are at a density of about 12 MW/km^2 (Sudarman et al. 1995), or half The Geysers' density. There is therefore less danger that these fields will duplicate The Geysers' history.

SUMMARY

Wellhead samples of steam cannot be used as samples of reservoir fluid without analysis of the physical processes during flow to the well.

Modelling the changes in gas content in wells in vapor-dominated reservoirs can give estimates of reservoir liquid saturation and porosity.

Gas concentrations are strongly dependent on flow rate. Determination of reservoir concentrations requires modelling of the changes during flow to the well. It should be normal practice to record flow rate as well as wellhead pressure with all chemical samples.

The "grid" method does not properly interpret samples taken from wells where there is flashing along the path to the wellbore. Variations in "y" are strongly affected by flow rate and kh, and are not simple measures of reservoir properties.

All methods depend upon ratios of gas concentrations, or changes in gas ratios (ie second-order differences). The results are sensitive to sampling or analysis error.

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NOTATION

B	gas distribution function
c_t	total fluid compressibility
K_1, K_2	chemical equilibrium constants
ln	natural logarithm
log	base 10 logarithm
S	saturation, fraction
W	mass flow of well, kg/s
x	(mole) fraction of gas in steam
y	fraction of reservoir steam in discharge
γ	defined function of saturation

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