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MODELING VAPOR DOMINATED SYSTEMS - SERRAZZANO

LUMPED PARAMETER MODELS

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## 1 - Introduction

Task 3/7 of the ENEL-DOE collaboration agreement has been devoted to numerical simulation of two-phase geothermal reservoirs. The work has been conducted by the National Geothermal Unit of ENEL, Italy and the Lawrence Berkeley Laboratory of University of California, USA.The National Research Council of Italy also contributed to the research.

The main objectives of the research were identified in improving the understanding of physical processes, investigating the theoretical bases of some simple reserve estimation methods and testing the feasibility of numerical simulation of a real vapor-dominated reservoir.

Natural geothermal reservoirs are found in a large variety of geologic and hydrogeologic conditions and are characterized by different distributions of the phases in the pore volume and fluid compositions.

The distribution of the phases in the reservoir affects to a large extent the production mechanism and the characteristics of the fluid produced (Refs.1,2).

The presence of noncondensable gas (mainly $CO_2$) also can be important in the control of reservoir performance (Refs. 3,4).

The fact that a reservoir delivers dry or even superheated steam does not exclude the possibility that the reservoir may also contain fluid in a liquid phase. In effect mass balance calculations for known vapor-dominated reservoirs show that the existence of a condensed phase must be admitted in order to justify the cumulative fluid production from the estimated reservoir volume (Refs. 2,5,6,7).

The experience of several exploited geothermal fields of New Zealand, Mexico and Italy show that fluid extraction can induce boiling inside reservoirs which were water-dominated in their undisturbed initial con

ditions. Thus it is likely that two-phase zones develop as a result of exploitation in the majority of exploited geothermal reservoirs.

Two major approaches have been followed in the mathematical mo delling of geothermal reservoirs: lumped parameter and distribu ted parameter models.

Lumped parameter models assume reservoirs and fluid properties uniform in space. Although such hypothesis represents a good appro ximation only for a few geothermal reservoirs, these models have been successfully applied in several reservoir engineering studies (Refs. 3,4,8,9,10,11).

Simple lumped parameter models are preferred when detailed re servoir information is not available or scarce, as it is for the majority of existing geothermal reservoirs.

Distributed parameter models can take into account complex re servoir shapes, etherogeneity, anhysotropy, irregular initial and boundary conditions ecc.

Although their use requires data which are generally difficult to obtain, they offer the possibility to study field behaviour well per well and carefully investigate phenomena controlled by fluid flow.

Distributed parameter models have been applied to Wairakei geo thermal field by several authors (Refs. 12,13,14), but up to date there has been no application to the simulation of the production history of an exploited vapor-dominated reservoir.

This paper presents some general results that can be obtained from lumped parameter models (PART 1) and the simulation of the va por-dominated reservoir of Serrazzano (PART 2) in Larderello field (Italy).

## 2 – Thermodynamic behavior of vapor dominated reservoirs

The most simple way to conceive a geothermal reservoir is to hypo thesise a "hot box", possibly adiabatic, containing three different components: rocks, water and noncondensable gas, assuming all the pro perties uniform through the box volume – Let us assume that thermal equilibrium persists between the three components with every process which may occur in the system, that no chemical reaction exists betwe en the components and that the gas is dissolved in the liquid phase according to Henry's law. Thus the changes of state are defined by the energy and mass conservation equations as follows.

(1)
$$\frac{d}{dt} \left( \mathcal{E}_a + \mathcal{E}_l + \mathcal{E}_g \right) = H_a G_a + H_i G_i + H_g G_g$$

(2)
$$\frac{d}{dt} M_a = G_a + G_i$$

(3)
$$\frac{d}{dt} M_g = G_g$$

Equations (1), (2) and (3) have been numerically integrated assu ming T, $\rho a$ and Pg as independent variables and assigning the total flow of the fluid extracted or injected. The liquid and steam produc tion rates have been calculated on the basis of their relative permea bilities $K_\ell$, Kv, defined analytically using a Corey's equation

$$K_\ell = (S_\ell^*)^4$$
$$K_v = (1 - S_\ell^{*2})(1 - S_\ell^*)^2$$

where

$$S_\ell = 1 - S$$
$$S_\ell^* = (S_\ell - S_{\ell r})/(1 - S_{\ell r} - S_{vr})$$

$S_{\ell r}$ = residual immobile liquid saturation

$S_{vr}$ = residual immobile vapor saturation

Capillary pressure and any adsorption phenomena have not been taken into consideration even though they could play an important role in the reservoir dynamics and in the reserve estimation.

Fig. 1 illustrates an ideal reservoir. This reservoir initially contains a large volume of vapor and a small volume of liquid water at boiling point. The fluid delivery is 40 Kg/sec and the water is presumed to be immobile.

Fig. 2 shows the change over a period of time of the total pressure and of the cumulative steam production.

The main characteristic of the pressure decline curve is given by the rapid decrease occurring in the first period of production due to the extraction of the noncondensable gas. This fast decrease ends when the gas pressure is very small and total pressure is close to that of saturation.

The variation of gas content and steam saturation are shown in Fig. 3.

The reservoir temperature decreases very slowly and obviously determines the vapor pressure as long as two phases are present in the reservoir. The slow decline in temperature signifies that the heat reserves are much greater than the heat required to vaporize the liquid contained in the reservoir.

It can be seen that after 5400 days (approx. 15 yrs) of production, 28% of the water stored in the reservoir has been produced causing a lowering in the temperature of only 3 °C. In the same period, the vapor saturation has changed from .80 to .86.

In practice, the reservoir engineer can never have complete information on the initial state of the reservoir. Thus, he will never have all the information that he needs to build a numerical model of the reservoir in order to predict its future evolution. However, after the reservoir has been in production for a certain period, infor

$$G = -40 \text{ Kg/s}$$
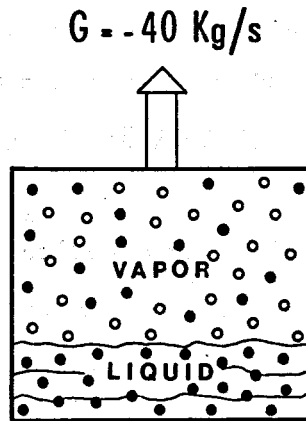


| | | |
|---|---|---|
| RESERVOIR VOLUME | $V$ | $= 4 \cdot 10^9 \text{ m}^3$ |
| POROSITY | $\phi$ | $= .07$ |
| SPECIFIC HEAT OF ROCK | $C_R$ | $= 1200 \text{ J/Kg}^\circ\text{C}$ |
| ROCK DENSITY | $\rho_R$ | $= 2500 \text{ Kg/m}^3$ |
| INITIAL STEAM SATURATION | $S_o$ | $= .8$ |
| INITIAL GAS PRESSURE | $P_{go}$ | $= 14.8 \text{ Bar}$ |
| INITIAL RESERVOIR TEMPERATURE | $T$ | $= 173^\circ\text{C}$ |
| INITIAL STEAM PRESSURE | $P_{vo}$ | $= 8.5 \text{ Bar}$ |

Fig. 1.  Initial and boundary conditions for the reservoir
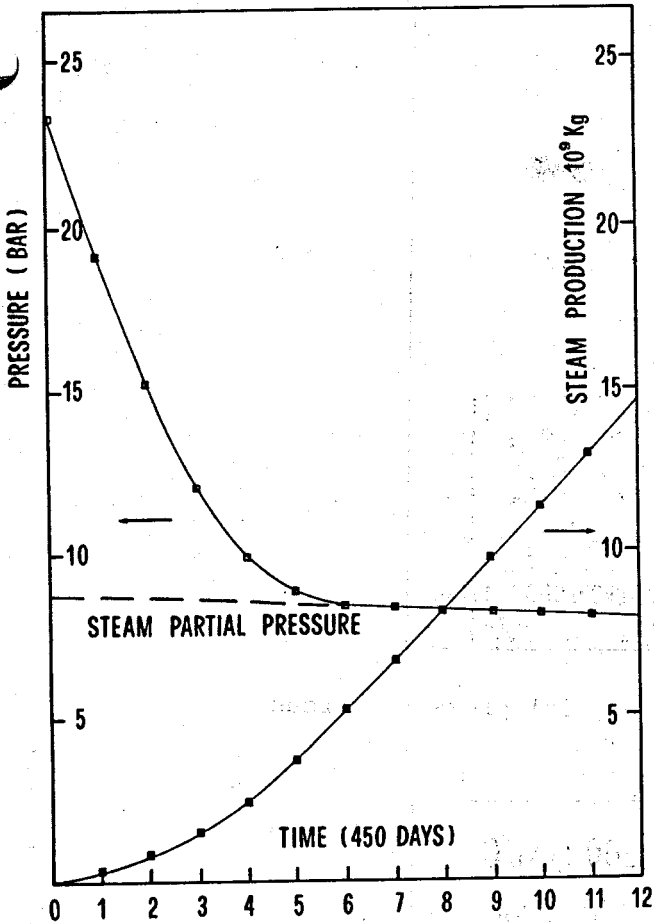         considered in this study.

Fig. 2.

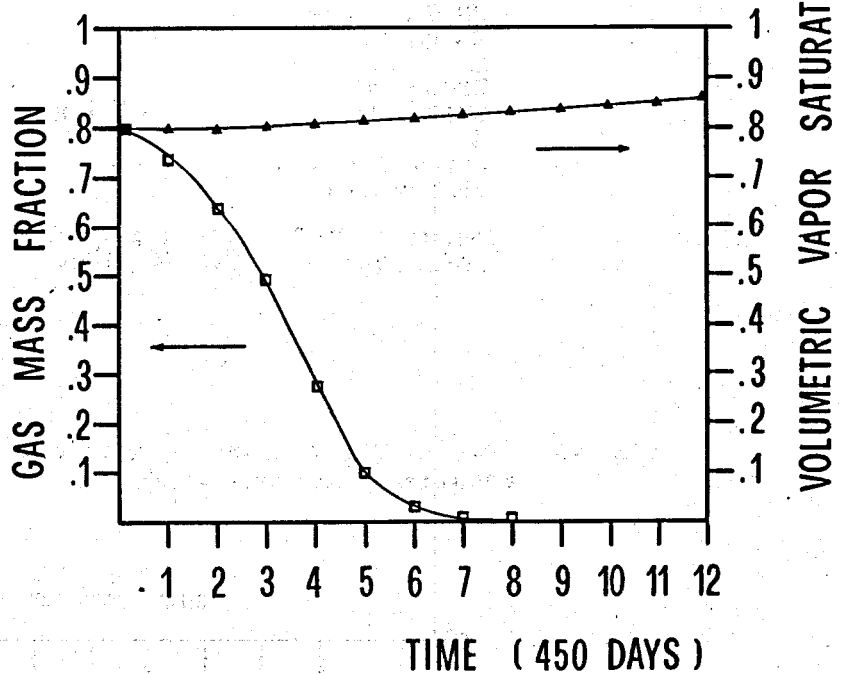Time behavior of the total pressure and of the steam production.

Fig. 3. Evolution of the gas mass fraction in the produced fluid and of the volumetric steam saturation during the reservoir depletion.
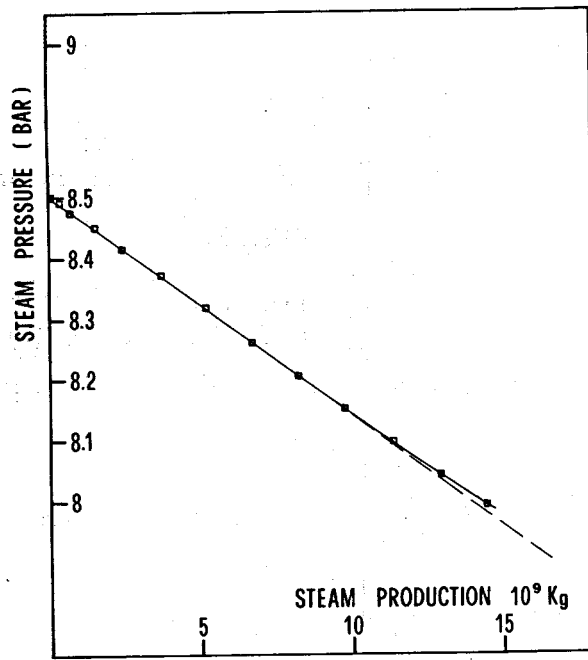
Fig. 4. Graph of the steam partial pressure versus steam production.
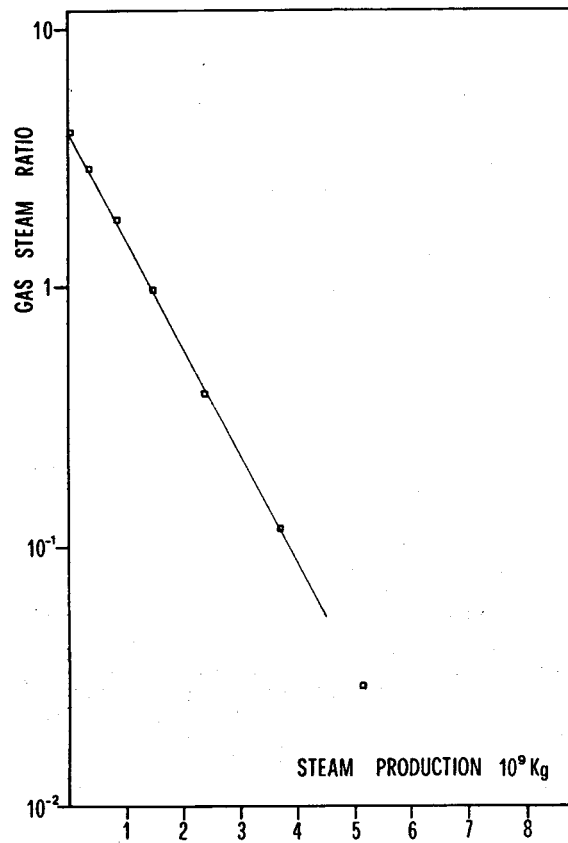


Fig. 5. Graph of the gas steam ratio versus steam production.

mation will be available for the flow rate and pressure which can be used to characterize the reservoir and maybe to estimate the re serves.

Figs. 2 and 3 show graphs that contain almost all the information necessary to evaluate the fluid reserves, once it has been establi shed that the reservoir being studied can be considered zero-dimen sional.

The rock energy decrease corresponding to a temperature decrease $\Delta T$ is

$$\Delta \mathcal{E}_{\iota} = (1 - \phi) V c_{\iota} \rho_{\iota} \Delta T$$

As most of the energy is contained in the rock rather than in the fluid, we can assume with a good approximation that this value must balance the energy spent to vaporize the fluid produced and the work performed on the fluid leaving the system

$$G_{a} (E_{v} - E_{\ell}) \Delta t + G_{a} (P/\rho_{v}) \Delta t$$

The result is

$$\Delta T = G_{a} \Delta t (H_{v} - E_{\ell}) / [(1-\phi) c_{\iota} \rho_{\iota} V]$$

or even

$$\Delta P = \left(\frac{dP}{dT}\right)_{s} \frac{G_{a} (H_{v} - E_{\ell}) \Delta t}{(1-\phi) c_{\iota} \rho_{\iota} V}$$

A more precise calculation, which still presumes that the energy of the fluid is negligible with respect to the rocks, gives the equa tion

$$\Delta P = \left(\frac{dP}{dT}\right)_{s} \frac{G_{a} (H_{v} - h(P))}{(1-\phi) c_{\iota} \rho_{\iota} V} \Delta t$$

where

$$\hbar(p) = \frac{E_\ell \ell_\ell - E_v \rho_v}{\rho_\ell - \rho_v} \qquad K(p) = \left(\frac{dP}{dT}\right)_s$$

This equation in practice gives the same results as the previous equation, as the vapor density is generally irrelevant compared with that of the liquid.

Finally, given that Hv, El and h (p) are functions which vary sli ghtly with respect to p, the significance of the previous equation is that pressure is almost a linear function of the mass produced. The slope of the plot of the pressure vs the cumulative steam production is approximately proportional to the inverse of the heat capacity of the rock. In practice, for a reservoir of this type, it is possible to evaluate the rock volume (if the density and specific heat are kno wn) by measuring the decrease in pressure or temperature corresponding to a given mass of vapor produced.

Using the results given in Fig. 1 and applying these concepts, the graph shown in Fig. 4 is obtained. Estimating that the average K (p) is between 8.5 and 8 bar and assuming for Hv-El, the value for the initial reservoir conditions, we obtain:

$$(1-\phi)V = 37.44 \; 10^8 m^3$$

which is in good agreement with the actual value of $37.20 \; 10^8 m^3$.

## 3 - Gas content decline

The previous thermodynamic considerations do not allow the calculation of fluid reserves.

However the gas, which is also present in the reservoir, at equilibrium conditions is much more concentrated in the vapor phase than in the liquid.

Thus, if fluid production also derives from boiling of the liquid present in the reservoir, the variation of gas content in the steam produced clearly depends on the amount of liquid initially in place.

Let $M_{gv}$ be the mass of gas in the vapor phase.

Assuming the temperature of the system to be almost constant, we have

$$\eta = \frac{\rho_{gv}}{\rho_v}$$

but

$$\frac{d}{dt}\eta = \frac{1}{\rho_v}\frac{1}{\phi V S}\frac{d}{dt}M_{gv}$$

where $M_{g\ell}$ is the mass of gas dissolved in the liquid.

Introducing the distribution coefficient $K_D$ which is dependent on temperature, and considering also that the vapor saturation varies very little during the time period being considered, we obtain

$$\frac{d}{dt}M_{g\ell} = (1-S)\phi V \frac{1}{K_D}\frac{\rho_\ell}{\rho_v}\frac{d}{dt}\rho_{gv} = (1-S)\phi V \frac{\rho_\ell}{K_D}\frac{d}{dt}\eta$$

or

$$\left[\phi V S \rho_v + (1-S)\phi V \rho_\ell \frac{1}{K_D}\right]\frac{d}{dt}\eta = \eta G_v = G_g$$

Therefore, for short time periods, there is a linear relationship between the logarithm of the gas/steam ratio and the cumulative steam production.Fig. 5 gives graph of $\ln \eta$ in function of the vapor produced. If the value of the quantity $\phi V$ is known, we can estimate S from the slope of the straight line shown in the figure, obtaining

$$S = .803$$

For vapor-dominated system in which S is quite large, usually the expression $(1-S)\rho_\ell /K_D$ can be ignored with respect to $\rho_v S$ and the product $\phi VS$ can thus be calculated directly.

In the example above, where S is quite large we obtain

$$\phi VS = .239 \; 10^9 \; m^3$$

while the actual value is $.224 \; 10^9 \; m^3$

Therefore, if the products $\phi VS$ and $(1-\phi) V$ are known, it is possible to estimate $(1-S)\phi V \rho_\ell$ i.e. the fluid reserves, evaluating V or $\phi$ by other methods, e.g. geophysical.

4 – Conclusions

The evolution of the temperature of a homogeneous two-phase geothermal reservoir is controlled exclusively by the vaporisation process. In vapor dominated system, the gas content of the fluid produced depends mainly on the volume fraction of the reservoir which was initially occupied by vapor.

Adopting these two concepts in the analysis of the evolution of the reservoir temperature and the gas/steam ratio it is possible to evaluate the fluid reserves.

Actually these concepts can only be applied in particular circum stances (Ref. 4). Normally the liquid water in a reservoir is not uniformly distributed, the reservoir is not homogeneous or isotro

pic, fluid properties are different from place to place and probably the assumptions concerning the gas are incomplete.

These factors can be taken into consideration with distributed parameter models.

## Nomenclature

| | | |
|---|---|---|
| $\xi$ | = Energy | Joule |
| H | = Specific enthalpy of fluid | Joule/Kg |
| $\mathcal{M}$ | = Mass | Kg |
| G | = Flow rate | Kg/s |
| | ($>0$ for injection, $<0$ for production) | |
| S | = Volumetric vapor saturation | |
| P | = Pressure | $N/m^2$ |
| T | = Temperature | °K |
| $\Delta t$ | = Time step | s |
| $\emptyset$ | = Rock porosity | |
| $C_R$ | = Specific heat of the reservoir rock | J/Kg°K |
| E | = Specific energy of fluid | J/Kg |
| $\rho$ | = Fluid density | $Kg/m^3$ |
| $\eta$ | = Gas – steam ratio | |
| $M_{gv}$ | = Mass of the gas in the vapor phase | Kg |
| $M_{gl}$ | = Mass of the gas in the liquid phase | Kg |

## Subscripts

| | | | | |
|---|---|---|---|---|
| a | = Water | | $\ell$ | = Liquid water |
| r | = Rock | | v | = Steam |
| g | = Gas | | gv | = Gas in vapor phase |
| i | = Injection | | gl | = Gas in liquid phase |

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