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NUMERICAL STUDIES OF ENTHALPY AND CO_2 TRANSIENTS IN TWO-PHASE WELLS

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Abstract

Numerical studies of enthalpy and CO_2 transients for wells completed in composite reservoir systems are carried out. Both constant rate and constant pressure production are considered. The results show that relatively small variations in hydrologic parameters and vapor saturation can have large effects on the enthalpy and CO_2 content of the produced fluids. Field data are presented that illustrate the theoretical results obtained.

Introduction

For wells penetrating a two-phase reservoir with both phases (liquid and steam) mobile, significant transient changes in enthalpy and CO_2 content of the produced fluids can occur. Model studies have shown that for a constant rate production the enthalpy will increase at early times and then stabilize (O'Sullivan, 1980; Sorey et al., 1980). The rise in flowing enthalpy depends on various factors such as porosity, permeability (or flow rate), initial vapor saturation and relative permeabilities (Sorey et al., 1980; Bodvarsson et al., 1980). Enthalpy increases of over 1000 kJ/kg have been observed for some wells completed in the Krafla reservoir in Iceland (Stefansson and Steingrimsson, 1980). Many wells which exhibit a large early enthalpy rise will show gradual decline in the long run.

In general, little is known about the transient behavior of non-condensible gases in produced fluids. Many reservoirs contain large amounts of noncondensible gases, particularly carbon dioxide (CO_2). Pritchett et al. (1981) studied the transient CO_2 content during discharge of a well completed in a homogeneous porous medium reservoir. They found that the CO_2 content of the produced fluids can not readily be correlated with the in-situ content, and may be either greater or less than that insitu. O'Sullivan et al. (1983) states that the CO_2 content of the produced fluids, like the enthalpy, will reach a stable value after an initial short transient period (see also Grant, 1979). They also found that the stable CO_2 content does primarily depend upon the initial partial pressure of CO_2, the relative permeability functions, and the initial vapor saturation. The effects of porosity and flow rate on the stable CO_2 content are secondary.

Grant and Glover (1984) present enthalpy and CO_2 transient data from well BR-21 in Broadlands, New Zealand. They investigate various models, including homogeneous porous medium and fracture models, in order to analyze the data. They conclude that the enthalpy transients can only be explained in terms of a fracture model because of the long period of enthalpy rise.

Most of the work to date on enthalpy and CO_2 transients has considered only constant rate testing in homogeneous porous media. The purpose of this paper is to investigate enthalpy and CO_2 transients in more heterogeneous formations, allowing for variable flow rates. Some of the questions to be addressed are:

(i) How do variations in hydrologic parameters such as porosity and permeability affect the stable enthalpy and CO_2 content?

(ii) Can enthalpy and CO_2 data give an estimate for the extent of the two phase zone?

(iii) How do enthalpy and CO^2 transients for constant pressure production differ from those observed during constant rate production?

In order to answer some of these questions, numerical modeling techniques are employed.

Approach

In the present work a single-layer radial model is used for the simulations. It is a composite reservoir model, with two zones of different hydrologic properties (porosity and permeability) or initial vapor saturation (Figure 1). The radial distance to the boundary between the two zones is fixed at r = 100 m. The reservoir parameters and initial conditions of the inner zone are the same in all simulations and are given in Table 1. Various different cases are considered where the properties of the outer zone are varied and the resulting enthalpy and CO_2 transients calculated. As a base case for comparison, the homogeneous reservoir case (identical properties of inner and outer zones) is modeled. In addition, the two extreme cases of no-flux and constant-pressure inner boundary (at r = 100 m) are simulated.

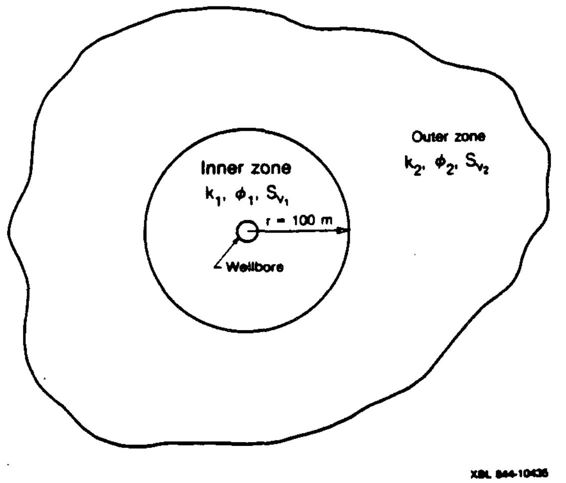

Figure 1. *Radial model for simulation studies.*

The mesh used consists of logarithmically-spaced elements with five elements per log cycle of radial distance. It extends to a radial distance of 4000 m, which is sufficient for simulating 1 year of production without outer boundary effects being felt. The pressure pulse travels slowly because of the high compressibility of two-phase mixtures (Grant and Sorey, 1979). A realistic wellbore radius of 0.1 m is used. In cases where the flow rate is assumed constant it is fixed at 0.15 kg/s·m. Linear relative permeability curves are used, with immobile liquid cutoff fixed at 0.65 vapor saturation and the residual steam cutoff at 0.05 vapor saturation. These relative permeability curves have been found to be consistent with production data from wells located at the Krafla field in Iceland (Pruess et al., 1983), as well as with the natural state conditions of the field (Bodvarsson et al., 1984). In the present work the multi-component simulator MULKOM (Pruess, 1983) is used, with an equation of state for H_2O-CO_2 mixtures developed by O'Sullivan et al. (1983).

Enthalpy transients - Constant Rate Production

In the first series of simulations, only the enthalpy transients are considered; the effects of non-condensible gases (CO_2) are neglected. The cases modeled are listed in Table 2. Note that for cases B through F all parameters are identical to those of the base case except for the parameter value given. The results obtained for the six cases are summarized in Figures 2-4.

Table 1. Reservoir parameters and initial conditions of the inner zone.

permeability:	1.5×10^{-14} m^2 (15 md)
porosity:	2 percent
rock density:	2650 kg/m^3
rock heat capacity:	1000 J/kg
thermal conductivity:	2.0 W/m.°C
initial pressure:	97 bars
initial vapor saturation:	0.10
initial partial pressure CO_2*:	10 bars

*Only used when CO_2 transients are considered.

If we first consider the base case, the figures show an early non-linear behavior in pressure during which the vapor saturation and the enthalpy rise. After that both the saturation and enthalpy stabilize, as one would expect for constant rate production (O'Sullivan, 1980; Sorey et al., 1980), and the pressure decline becomes near-linear on the semilog time plot. Note also in Figure 4 that the enthalpy rise occurs very early because of the rapid thermal equilibrium in porous media. Enthalpy transients for wells completed in fractured reservoirs can last much longer (Grant and Glover, 1984). Also, in many cases the enthalpy transients may be prolonged because of non-uniform vapor saturation conditions near wells when they first come on line, if drilling fluids and injected water remain in the vicinity of the well during the heating-up period (Pruess et al., 1983).

As shown in Figures 2-4, all of the cases (except for case G) show identical response until the effects of the outer zone are felt (radius of influence exceeds 100 m). For the no-flux boundary conditions (case B) the results are as expected; a rapid pressure decline along with a rapid increase in vapor saturation and enthalpy of the produced fluids is observed. Also as expected, the effect of the constant pressure boundary is to stabilize the well pressure and lower the vapor saturation and flowing enthalpy, since the recharge enthalpy from the boundary will equal the initial flowing enthalpy in the system. When the outer zone has a higher initial vapor saturation (case C) the pressure decline is slightly higher than that of the base case, due to the reduced overall mobility caused by the increasing vapor saturation. The enthalpy reaches a stable value that is identical to that observed if the vapor saturation is initially 20% everywhere.

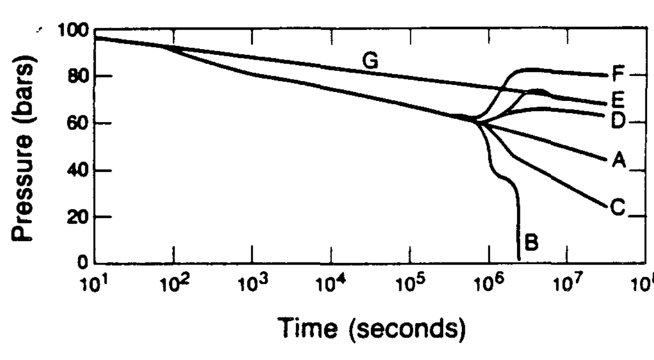

Figure 2. Constant rate production. Pressure variation with time for the different cases.

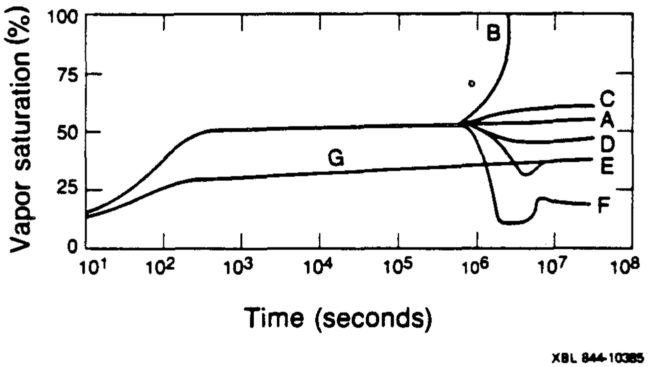

Figure 3. Constant rate production. Vapor saturation variations with time for the different cases.

The effects of porosity and permeability on enthalpy transients were studied by Sorey et al. (1980) and Bodvarsson et al. (1980). In general, the rise in enthalpy is inversely proportional to permeability but directly proportional to $(1-\phi)/\phi$, where ϕ is the porosity (Bodvarsson et al., 1980). This is evident in Figures 2-4, as both doubling the permeability and increasing the porosity of the outer zone causes a large decrease in the stable enthalpy. Note also the large increase in the pressure at the well due to the increased fluid mobility associated with lower vapor saturation.

In case G the porosity is fixed at 0.10 over the entire reservoir. Because of this higher porosity, the vapor saturation and enthalpy rise are much less, as evidenced in Figures 3 and 4. However, it is interesting to note that the long term behavior of this case is identical to case E (inner region porosity of $\phi = 0.02$). This implies that the long-term flow characteristics of a well are independent of the near-well porosity, although it dominates the early time enthalpy rise. This is not the case with permeability, since the pressure decline at the well reflects the harmonic mean permeability of all rocks within the radius of influence.

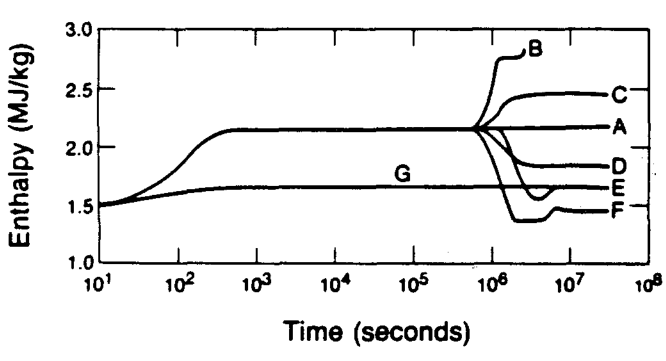

Figure 4. Constant rate production. Enthalpy variations with time for the different cases.

Table 2. Different cases simulated.

Case	Value for outer zone/boundary conditions
A	base case
B	no-flux boundary (r = 100 m)
C	initial vapor saturation: .20
D	permeability: 30 md
E	porosity: 0.10
F	constant pressure boundary (r = 100 m)
G	porosity: 0.10 everywhere

In summary, spatial variations in porosity, permeability and vapor saturation can greatly effect the enthalpy of the produced fluids. Proper analysis of such enthalpy transient data may give useful information on reservoir conditions; for example, the extent of two-phase zones. Because of uncertainties regarding relative permeabilities, the enthalpy transients cannot give quantitative information on changes in the hydraulic parameters. However, the radial distance to the discontinuity can be estimated from the equation for the radius of influence (Earlougher, 1977):

$$r = \sqrt{4 \alpha t} \tag{1}$$

where t is the time when enthalpy changes due to the presence of the discontinuity and α is the hydraulic diffusivity. The hydraulic diffusivity for two-phase mixtures is given by Grant and Sorey (1979). It can be estimated from pressure transient data, although such estimates are generally not very accurate (Sorey et al., 1980). We have also found that applying equation (1) to the simulated data gives only a very coarse estimate of the radial distance to the discontinuity.

Constant Pressure Production

In the last section a constant flow rate is assumed, but in most cases geothermal wells are produced at constant downhole pressure. Here we neglect the effects of enthalpy variations on the downhole pressure. In order to model constant pressure production a deliverability model is used, where the flow rate (q_t) at any time is calculated based upon the productivity index PI and the bottomhole pressure P_{wb}:

$$q_t = \sum_{\beta = \text{liquid, vapor}} \frac{k_{r_\beta}}{\mu_\beta} \cdot \rho_\beta \cdot PI \cdot (p_\beta - p_{wb}) \; . \tag{2}$$

Here k_{r_β} is the relative permeability of the β phase, μ_β is its dynamic viscosity and ρ_β the density. p_β is the pressure in the well element. In the simulations the values used for the bottomhole pressure and the productivity index are 35 bars and 4×10^{-14} m^3, respectively.

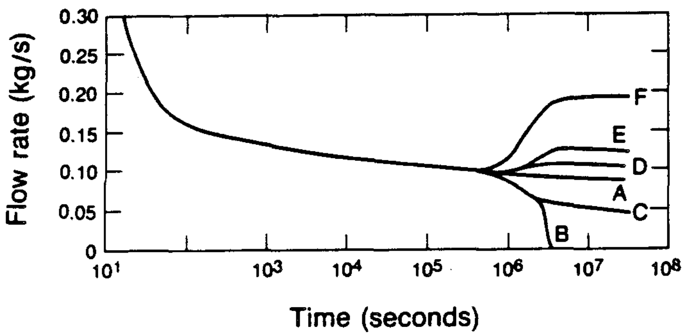

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Figure 5. Constant pressure production. Flow rate variations with time for the different cases.

The same cases are simulated as those modeled using the constant flow rate (Table 2), except for case G. The results are shown in Figures 5-8. Because of the constant downhole pressure, the flow rate will initially be high and then decline with time. The high initial flow rate results in early peaks in vapor saturation and enthalpy, but then both gradually decline due to the decreasing flow rates (Figures 7 and 8). The enthalpy never quite stabilizes as in the case with constant rate production (Figure 4).

When one compares the results for the different cases it is interesting to note that the well element pressure is practically identical for all cases with the exception of the two extreme cases (no-flux and constant pressure boundary). In the closed boundary case (case B), the pressure falls to the well bottomhole pressure (35 bars) soon after the effects of the boundary are felt, and the flow rate falls to zero. In the constant pressure boundary case, the flow rate drastically increases when the boundary is felt and the vapor saturation decreases (low enthalpy inflow from the boundary). The enthalpy declines steeply as for the constant rate case and stabilizes at the value of the recharge enthalpy from the boundary. For all other cases (cases C, D and E) the results are similar to those obtained using the constant rate production except that stable enthalpy values are never reached.

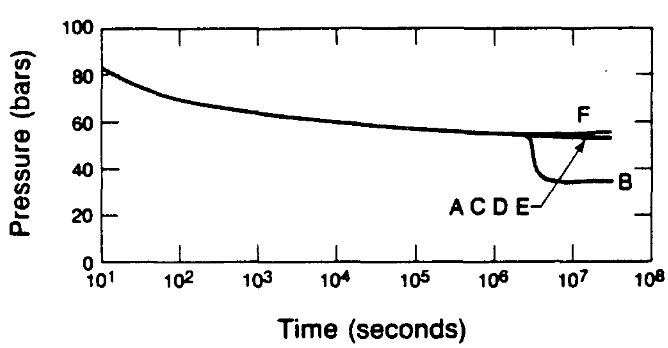

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Figure 6. Constant pressure production. Pressure variations with time for the different cases.

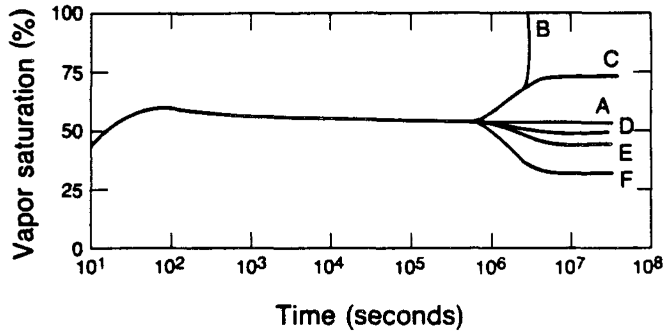

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Figure 7. Constant pressure production. Vapor saturation variations with time for the different cases.

CO_2 Transients

In the simulations with CO_2, a partial pressure of CO_2 of 10 bars is assumed; this corresponds to approximately 0.008% CO_2 per mass, which is the estimated CO_2 content of reservoir fluids at the Baca field, New Mexico (Pritchett et al., 1981). The production is again modeled using the deliverability model, but this time with a five-times greater productivity index (PI = 2×10^{-13} m^3). The presence of CO_2 reduces greatly the rise in enthalpy of the produced fluids, so that the productivity index is increased in order to obtain a reasonable rise in enthalpy. Again the same cases as those listed in Table 2 are simulated (with the exception of case G). The computed flow rates, enthalpies and CO_2 content of the produced fluids are given in Figures 9-11. In general the figures show much smaller variations in enthalpy and flow rates between cases than when no gas is present (Figures 5-8). The presence of the gas compresses changes in enthalpy which in turn result in smaller mobility changes and consequently smaller flow rate changes. In general, the enthalpy and flow rate transients for the different cases are consistent with those obtained without the gas.

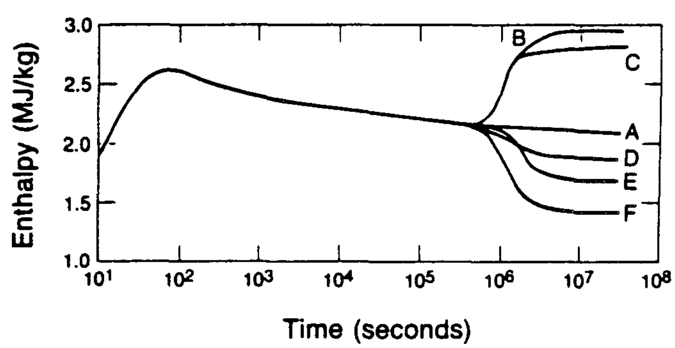

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Figure 8. Constant pressure production. Enthalpy variations with time for the different cases.

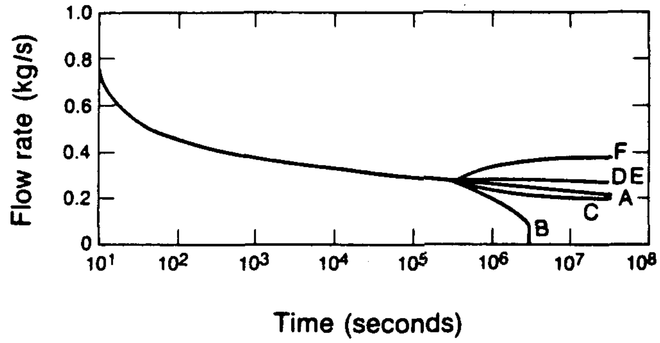

Figure 9. Constant pressure production with CO_2. Flow rate variations with time for the different cases.

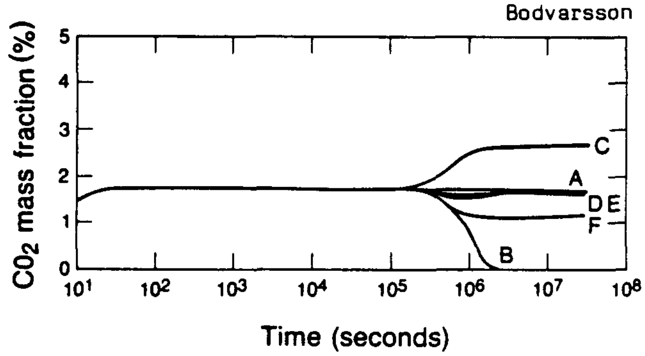

Figure 11. Constant pressure production with CO_2. CO_2 content variations with time for the different cases.

Figure 11 shows that for the base case stable CO_2 content exceeds that in-situ; the rise in the CO_2 content is 0.5 percent. In case of the closed reservoir (case B) the CO_2 content goes to zero when the vapor saturation approaches unity. On the other hand, the CO_2 content increases greatly when the effects of the higher vapor saturation in the outer zone are felt (case C). In this case the stable CO_2 content increases 1.1% for only a 0.1 change in the initial vapor saturation. This is due to the low solubility of CO_2 in the liquid phase; most of the CO_2 is in the gas phase. Also of interest is the fact that the stable CO_2 content does not significantly depend upon the porosity and permeability of the medium. This is consistent with results of O'Sullivan et al. (1983). Theoretically this implies that careful monitoring of enthalpy and CO_2 content of the produced fluids can help identify radial vapor saturation changes or changes in hydrologic parameters. If the enthalpy changes, but the CO_2 content remains the same, spatial variations in the hydrologic parameters may be the cause. However, if the CO_2 content also changes, this would imply spatial changes in vapor saturation.

Field Data

Reliable enthalpy and CO_2 transient data from two-phase reservoirs is scarce. Probably, the best data available are those from well BR-21 at Broadlands, New Zealand (Grant and Glover, 1984). Figure 12 shows the downhole pressure, enthalpy and CO_2 data for one period of the test; the flow rate is kept constant during this period. The enthalpy transients occur at rather late time, which may indicate fracture effects (Grant and Glover, 1984). The figure also shows an apparent radial change in vapor saturation, starting at approximately 7000 minutes. This causes an additional rise in both enthalpy and CO_2 content of the produced fluids. The pressure decline also increases due to the lower mobility of the reservoir fluids at higher vapor saturation. Note that the changes in enthalpy cannot be explained by changes in hydrologic parameters because the CO_2 content also changes.

A coarse estimate of the radial distance to the discontinuity in vapor saturation can be made using the data shown in Figure 12. Assuming zero skin, one can estimate the hydraulic diffusivity, α, from the zero drawdown intercept of the pressure transient data. This yields a value of $\alpha = 4 \times 10^4$ m^2/s, which is reasonable for a 260°C feed. Then using the transition time (t = 7000 minutes) and equation 1, the radius to the discontinuity of 13 meters can be calculated.

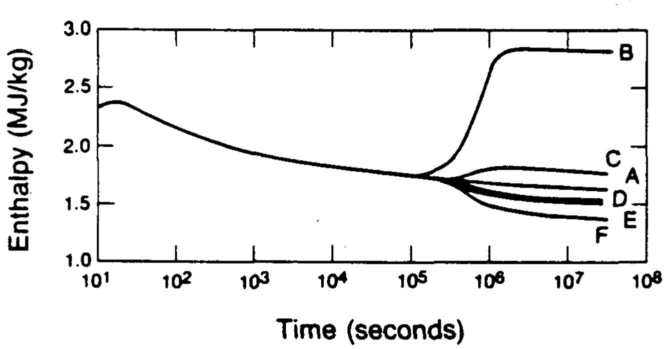

Figure 10. Constant pressure production with CO_2. Enthalpy variations with time for the different cases.

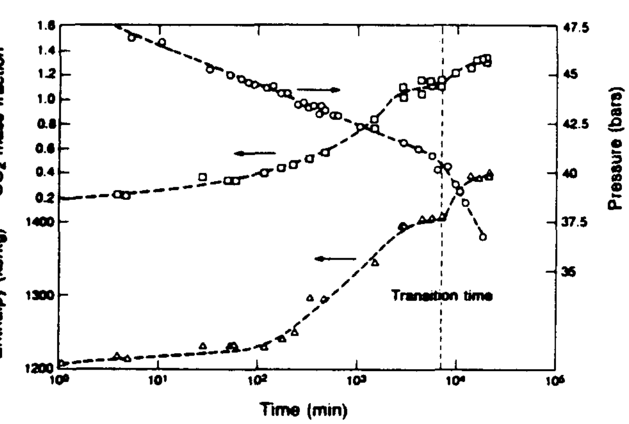

Figure 12. Downhole pressure, CO_2 content and enthalpy variations with time for well BR-21 (from Grant and Glover, 1984).

Note that in the absence of enthalpy and CO_2 transient data we would probably interpret the changing slope in the pressure transient data in terms of a barrier boundary. However, no such boundaries are present in earlier flow test data (Grant and Glover, 1984).

Conclusions

From the numerical simulation studies the following conclusions can be made:

1. Radial variations in hydrologic parameters and vapor saturation have large effects on the enthalpy of the produced fluids.

2. The near-well porosity and vapor saturation have strong effects on the rise in flowing enthalpy, but the long-term stable enthalpy is independent of both.

3. The enthalpy transients for a well produced at a constant bottomhole pressure show a sharp initial rise due to high flow rates, but a gradual decline thereafter. This is consistent with data from many geothermal wells.

4. Radial variations in hydrologic parameters cause rapid changes in flow rates for wells produced at constant pressure. Most of the flow rate changes are due to mobility effects.

5. Radial variations in vapor (gas) saturation have large effects on the CO_2 content of produced fluids, but it is unaffected by variations in permeability and porosity.

6. Careful monitoring of both enthalpy and CO_2 content of produced fluids may help determine the extent of two phase zones and variations in hydrologic parameters.

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