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ANALYSIS OF PRESSURE, ENTHALPY AND CO_2 TRANSIENTS IN WELL BR21, OHAAKI, NEW ZEALAND

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ABSTRACT

Numerical studies are undertaken, which incorporate both double porosity and noncondensible gas effects, to determine the characteristics of the reservoir near well BR21 of Ohaaki geothermal field, New Zealand. It is shown that the application of numerical techniques to analyse two-phase well data can provide valuable information that may not otherwise be obtained. Numerical techniques allow more of the true reservoir complexities to be included, futher constraining the results. The model developed adequately matches observed pressure, enthalpy and flowing CO_2 mass fraction while providing estimates of important reservoir parameters.

INTRODUCTION

Interpretation of data from wells completed in two-phase fractured geothermal reservoirs is difficult because methods available for analysis of such data are limited. In most cases methods developed for single-phase porous media reservoirs are modified to take into account enthalpy variations and relative permeability effects. It is well known that the application of these methods may yield very unreliable results for important reservoir parameters.

Interpretation of two-phase well data using numerical techniques may yield more reliable results because more of the true reservoir complexities can be introduced into the analysis. In addition to the multi-phase effects on such data, we can also model the fractured nature of the reservoir and the effects of noncondensible gases and dissolved solids, if those are considered important. Actually, it may be beneficial to consider multi-component effects, because these may constrain the results, giving a better representation of the true system.

Data are available for Ohaaki geothermal field, New Zealand, well BR21 which will allow for the interpretation of the near-well reservoir parameters. For a two week period, the well was opened to a constant throttle while the transient changes in downhole pressure, discharge enthalpy, and flowing mass fraction of CO_2 were monitored. The flowrate during this period was about 25 kg/s.

The data are typical of two-phase systems showing large variations in enthalpy and flowing mass fraction of CO_2 (see Figure 1). In addition, there is an extended transient period before the enthalpy and mass fraction of CO_2 stabilize, suggesting that the well response is dominated by the fracture-matrix effects rather than behaving as a porous medium. (Grant and Glover, 1984).

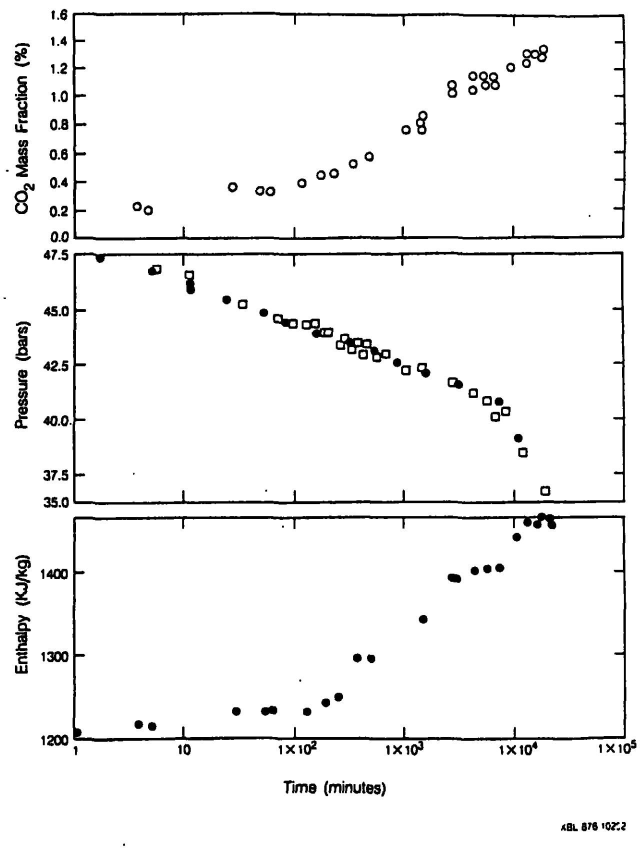

Figure 1. Changes in the downhole pressure, flowing mass fraction of CO_2, and flowing enthalpy for well BR21, Broadlands, New Zealand (Grant and Glover, 1984).

Results from numerical simulations are shown to aid in the interpretation of the data from well BR21. A match with the pressure, enthalpy, and mass fraction of CO_2 provides insight into the reservoir conditions in situ. The analysis of CO_2 transients is shown to be valuable in the interpretation of reservoir parameters affecting the performance of two-phase wells.

RESERVOIR AND WELL DESCRIPTION

Ohaaki is currently under development for 110 MW electrical power production. To date, over thirty wells have been drilled at the site. Extensive well testing has occured at Ohaaki and a large data set exists. The field is a "hot-water" system containing a significant amount of noncondensible gas (carbon dioxide). The extent of two-phase zones is not known. The exact amount of gas present within the reservoir is still debated although the general concensus is that the reservoir fluid contains between 2 to 4 percent CO_2 by weight (Grant, 1977; Sutton and McNabb, 1977; Grant and Glover, 1984). Total well discharges show noncondensible gas fractions between 0.5 and 10 percent by mass (Grant, 1977).

Well BR21 was drilled in 1970 to a depth of 1120 m; the casing extended to 425 m. The location of the well and the major faults is shown in Figure 2. In 1971, during the initial discharge period, the BR21 fluid contained 4.8 percent gas by weight. Later, however, during a flow test in 1975 the gas content was down to 1.9 percent by weight. BR21 is a two-phase well producing fluids with enthalpy in excess of that for a saturated liquid under reservoir conditions. There are permeable zones at 500 m and at 800 to 900 m, however, the upper zone "dominates" during discharge (Grant and Glover, 1984). The lower zone produces fluids at a temperature of 270 °C. The temperature of the upper zone is believed to be 255 °C, however, because of upflow from the lower zone into the upper one the exact temperature is not known. The upper zone has an injectivity of 15 kg/bar·s and a productivity of 1.5 kg/bar·s. The lower zone is not as permeable, its corresponding values of 1.5 kg/bar·s and 0.3 kg/bar·s (Grant and Glover, 1984).

A simplified cross section for the area near BR21 is shown in Figure 3 (Ministry of Works and Development, 1977). It should be noted that the main feedzone of the well (at 500 m depth) is located close to a fault, but the fault is not thought to be the primary source of fluid (Ministry of Works and Development, 1977). The major feedzone is located in the Waiora Formation, a pumiceous lapilli tuff which is locally water-laid and with a low quartz content (Ministry of Works and Development, 1977). Overlying the Waiora Formation is the dense and largely impermeable Ohaki Rhyolite. The unit directly below the Waiora Formation is the very dense Broadlands Dacite which has low permeability. The lower feedzone is located in the Rautawiri Breccia, a lithic tuff. The permeability of this tuff is thought to be largely along the contacts. It is separated from the Waiora Formation by the Broadlands Dacite above. The bottom of well BR21 is located in the Rangitaiki Ignimbrite, a low permeability quartz-plagioclase welded vitric tuff.

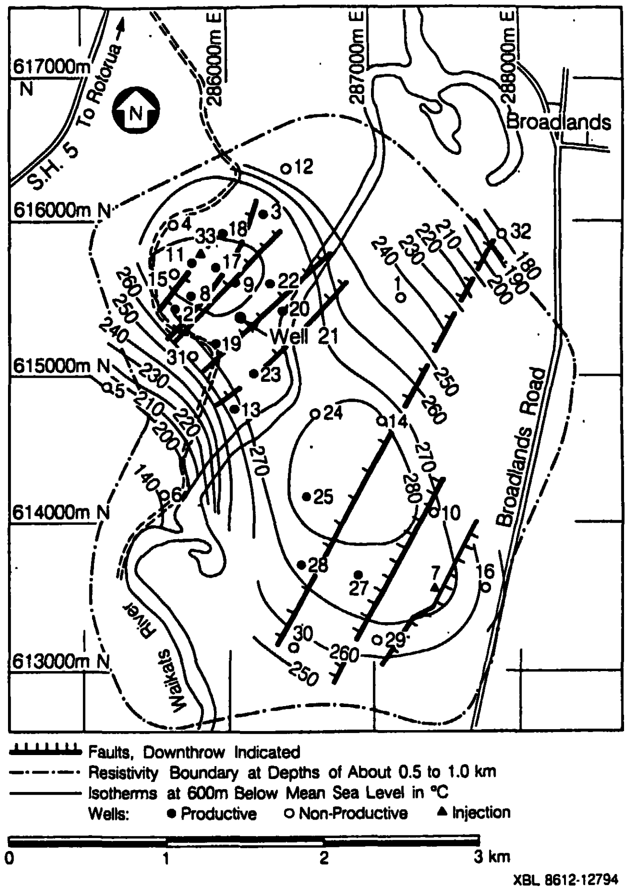

Figure 2. Location map of wells showing major faults and the temperature contours in Broadlands geothermal field, New Zealand (Ministry of Works and Development, 1977).

PREVIOUS ANALYSIS

Grant and Glover (1984) carried out an extensive analysis of BR21 data using analytical techniques developed by Grant (1979). They noted that the enthalpy took several weeks to stabilize while the pressure transients lasted only for minutes or even seconds. Assuming reasonable reservoir parameters, they determined that the enthalpy transient period should be on the order of minutes for a porous medium. From this Grant and Glover concluded that a fractured medium was required to explain the enthalpy transients. A fracture model with impermeable matrix blocks was used to match the pressure and enthalpy transients. The time necessary for stabilizing the enthalpy transients was assumed to be equal to the time required for thermal equilibrium to be established between the fracture fluids and the impermeable matrix blocks. They calculated a "relaxation time" for conductive equilibrium, estimating for 1 to 2 m^3 matrix blocks, a relaxation time of between 400 and 1000 hours. Analysis of the chemical transients was determined to be too complex to include in their study (Grant and Glover, 1984).

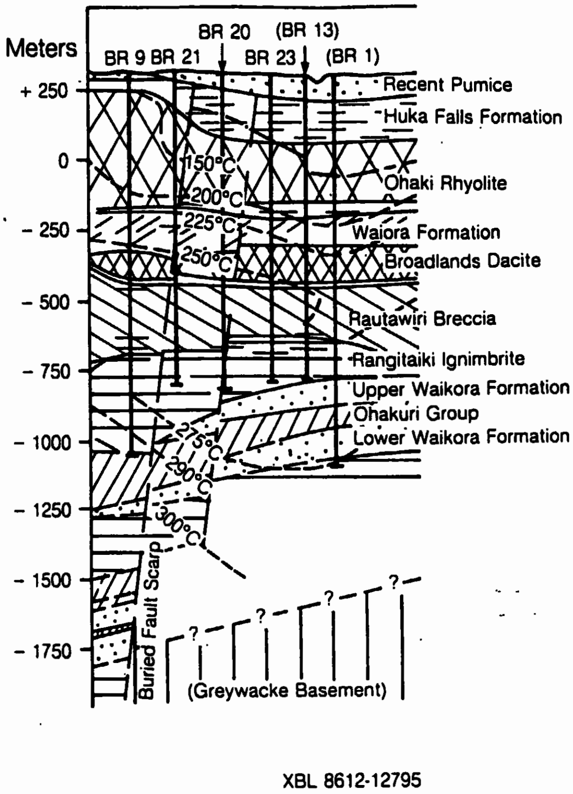

Figure 3. Cross section showing the geology surrounding well BR21, Broadlands geothermal field, New Zealand (Ministry of Works and Development, 1977).

Table (1). Model Reservoir Parameters.

Parameter	Reservoir Value(s)
reservoir thickness	100 m
wellbore radius	0.12 m
flowrate	25 kg/s
fracture spacing	30 m
fracture porosity	0.1%
matrix porosity	18%
fracture transmissivity	10.0 Dm from well to 125 m 1.0 Dm beyond 125 m
matrix permeability	0.3 md
thermal conductivity	2.2 W/m °C
rock heat capacity	1000 J/kg °C
rock density	2650 kg/m^3
fracture relative permeability	X-curves S_{rl}=.0 S_{rg}=.0
matrix relative permeability	X-curves S_{rl}=.05 S_{rg}=.40
initial total pressure	50-bars
initial gas saturation	6% in fracture to 70 m 15% in fracture beyond 70 m 33% in matrix
initial partial pressure of CO_2	2.0 bars
intial temperature	≈260 °C
diffusion coefficient	1.38x10^{-5}m^2
tortuosity	0.25m/m

PRESENT ANALYSIS

Numerical studies were undertaken to determine the characteristics of the reservoir near well BR21, using the simulator MULKOM (Pruess, 1982) with an equation of state for H_2O–CO_2 mixtures developed by O'Sullivan et al. (1983), The upper feedzone in the well was assumed to provide all of the fluid during production and, hence, a single layer radially infinite model was used. The mesh consisted of logarithmically discretised elements with five elements per cycle extending to a radial distance which was sufficiently far from the well so that boundary effects would not be felt during the simulations. The MINC method (Pruess and Narasimhan, 1982) was used to approximate the fractured nature of the reservoir with the matrix being discretised into five nested elements. The effective thickness of the reservoir was assumed to be 100 m by inspection of the cross section. This is the approximate thickness of the Waiora Formation in the vicinity of well BR21. The reservoir had initially 50 bars total pressure at the primary feed zone and the well was produced at a constant rate of 25 kg/s. The relative permeability functions used in these simulations are linear but different functions are used for the fractures and the matrix blocks. The relative permability curves for the fractures are assumed to have no cutoffs whereas the matrix curves have a residual liquid saturation of 40 percent and a 5 percent residual gas saturation. Other rock and fluid parameters used in the simulations are given in Table 1.

The "best" match with the BR21 pressure, enthalpy, and mass fraction of CO_2 transient data is shown in Figure 4. We found that a composite reservoir model is necessary to match the data (Figure 5). The early transients are dominated by the properties of the fracture system. The rapid decline in pressure without a concurrent rise in enthalpy (see Figure 4) indicates that the fracture storage is small and that the fractures are fairly permeable. For the 100 m thick reservoir, we found that a fracture porosity of 0.5% was needed to provide the appropriate short term storage effects. Here, fracture porosity is defined as the total volume occupied by the fractures in a unit volume of rock. Typical fracture porosities range from 0.1 to 1.0% so that the value of 0.5% deduced from the modeling appears reasonable. Near the well a fracture transmissivity of 10 Dm provides a reasonable match with the pressure transient data. The steeper decline at later time (after 5 x 10^5 seconds) necessitates smaller transmissivities away from the well. The best match was obtained when an outer region with a 1 Dm transmissivity was used 125 m away from the well (see Figure 5).

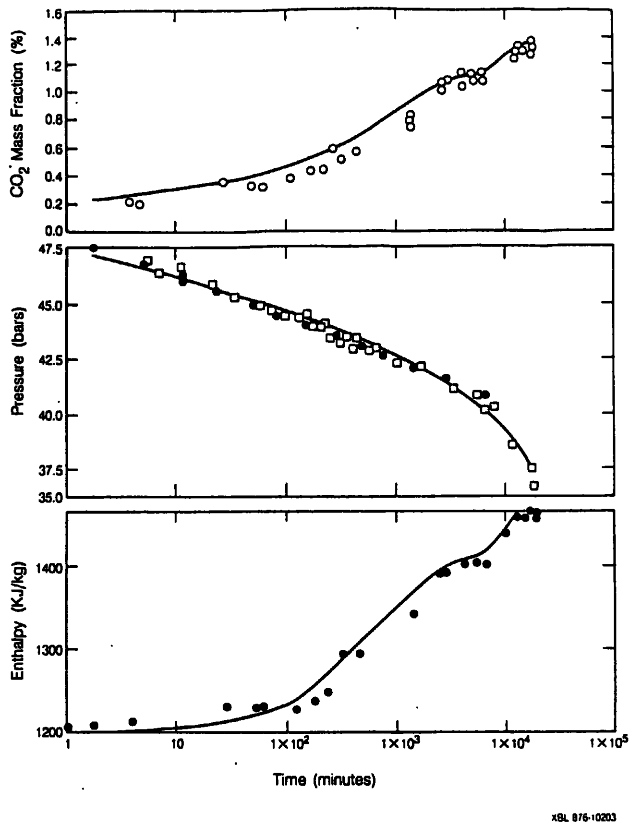

Figure 4. Comparison of best fit model (lines) to measured results (points) of changes in downhole pressure, flowing mass fraction of CO_2, and flowing enthalpy with time

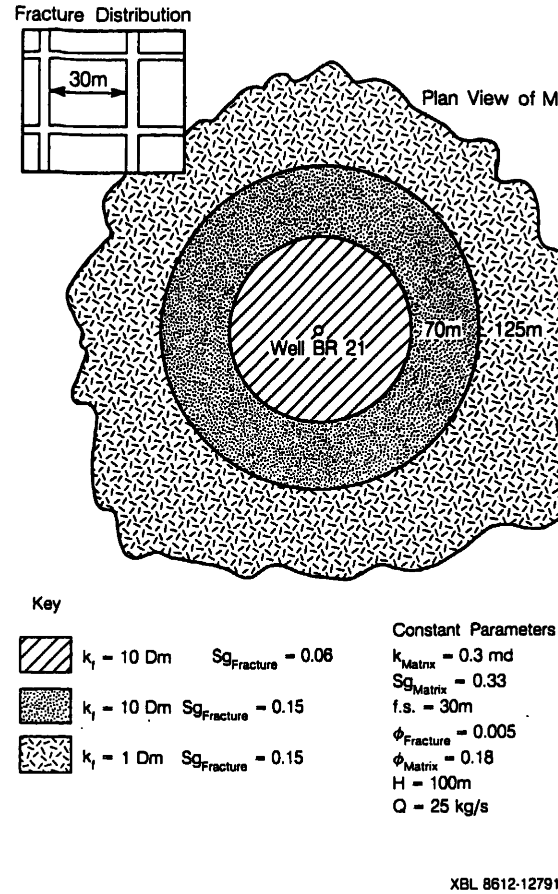

Figure 5. Diagram of best fit model including important reservoir and fluid parameters.

The initial gas saturation assumed in the fractures near the well is 6 percent so that the computed initial flowing enthalpy matches the observed one (1190 kJ/kg). A 2 bar initial partial pressure of CO_2 was used, which along with an initial gas saturation of 6% gives the observed early time mass fraction of CO_2 of 0.28% (see Figure 4). Different values for the initial gas saturation and the partial pressure of CO_2 will not only result in incorrect initial enthalpy and mass fraction of CO_2 but, also the pressure decline will not match the observed one.

With the initial conditions met one must consider the observed rise in both enthalpy and flowing CO_2 mass fraction. An increase of gas saturation away from the well is required in order for both the enthalpy and the mass fraction of CO_2 to rise (Bodvarsson, 1984). The initial stablilized value of both the enthalpy and the flowing CO_2 mass fraction at about 7000 minutes helps to determine two other parameters, matrix gas saturation and porosity. The enthalpy of approximately 1400 kJ/kg is representative of the equilibrium fluid enthalpy between the fractures and the matrix. Therefore, this value helps establish the required gas saturation in the matrix, which was determined to be about 33 percent. The matrix porosity has been shown to have strong effects on the rise in the flowing mass fraction of CO_2 without significantly affecting the enthalpy (Gaulke, 1986). An assumed matrix porosity of 18 percent provided sufficient CO_2 to cause an increase in the CO_2 mass fraction to 1.1 percent as observed. This matrix porosity would seem rather high except that the rock is pumiceous suggesting a large void volume.

The time delay in the rise of both the enthalpy and the CO_2 flowing mass fraction is controlled primarily by two parameters. The fracture spacing is proportional to the surface area between the fractures and the matrix and, hence, will control the rate at which equilibrium flow of heat and mass is established between the fracture and matrix. In addition, the matrix permeability controls the amount of fluids recharging the fractures from the matrix. Using a simple trial and error method it is easily established that the fracture spacing needed to cause the time delay before the rise in enthalpy and CO_2 content, is about 30 m. The matrix permeability which provides fluid at a rate necessary to enhance the enthalpy and flowing CO_2 mass fraction is 0.3 millidarcy. Actually, the matrix-fracture interaction is proportional to k_m/D^2 where k_m is the matrix permeability and D^2 is the square of the fracture spacing (Bodvarsson and Witherspoon, 1985). Thus, different values for k_m and D^2 are possible as long as the ratio k_m/D^2 is about 3×10^{-19}. However, the values for D of 30 m and and k_m of 0.3 md seem reasonable.

The final consideration here is the moderate rise in both the flowing enthalpy and the flowing mass fraction of CO_2 accompanying the steep pressure drop at late times (after about five days). If only the enthalpy and the pressure are considered, this response would be characteristic of boundary effects. However, since the flowing CO_2 mass fraction also rises, boundary effects are not sufficient by themselves to explain the changes (Bodvarsson, 1984). Therefore, a combination of changes in the gas saturation and fracture permeability are required to accurately match these data. The pressure pulse travels along the fracture more rapidly than the hydrodynamic front. This indicates that changes in gas saturation are needed closer to the well than changes in fracture permeability in order to match transient conditions. Thus the gas saturation in the fracture is increased to 15 percent from 6 percent at 70 m, while the fracture transmissivity decreases from 10 Dm to 1 Dm, at about 125 m. This allows the increase in the pressure decline to be felt at the well at the same time as the changes in the fluid composition and thermodynamic conditions.

CONCLUSIONS

A model of well BR21 has been developed that adequately matches observed pressure, enthalpy, and flowing CO_2 mass fraction data. This model is the result of trial-and-error numerical simulation studies. From the available data it was possible to estimate various reservoir parameters which seem reasonable given the field conditions at Ohaaki.

The transmissivity of the fracture system near the well is estimated to be 10 Dm and 1 Dm further away from the well (125 m). Matrix permeability is estimated to be about 0.3 md and average fracture spacing 30 m. Average fracture porosity is estimated to be 0.5% and matrix porosity 18%. The gas saturation in the fracture system as determined from this study is 6% near the well and 15% away from it, which is consistent with the fact that the well was flowing for some time before the flow test. The matrix gas saturation is estimated to be about 30% and the initial CO_2 partial pressure 2 bars. It should be noted that these values are dependant on the assumed relative permeability curves. However, the values obtained for very important reservoir parameters indicates the value of multi-component modeling of well test data. Modeling of multicomponent changes give additional constraints on modeling results.

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