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A SIMPLE MODEL OF THE OHAAKI GEOTHERMAL RESERVOIR

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ABSTRACT

As the first stage of a modelling study of the Broadlands geothennal field a simple model of the main upflow zone of the western (Ohaaki) part of the field has been developed. The model which has the form of a vertical column with lateral recharge can simulate a natural state which is close to that observed and it produces a good fit to the observed history during the 1966–1974 period of high production followed by low production.

INTRODUCTION

The Broadlands geothermal field in New Zealand has been under investigation for over two decades. To date over 40 wells have been drilled in the area–mostly during the period 1966–1970. (See Ministry of Works 1977) The wells have identified the presence of a high-temperature (up to 300°C) two-phase reservoir (Bixley, 1976) with substantial quantities of noncondensible gases, primarily CO_2 (Grant, 1977a,b). A power plant with a capacity of 100MWe is currently under construction.

At Broadlands there was little apparent geothermal activity at the surface. There was one major hot spring in the area, Ohaaki Pool, which discharged approximately 10kg/s before significant discharge of the wells occurred. The overflow from the Ohaaki pool (or its water level when it is not full) responds to changes in production fran the shallow wells indicating that it is fed from the rhyolite formation (Grant, 1982). Some steam vents are also present. During the period 1966-71 many of the Broadlands wells were discharged with a total of 35Mt of fluid removed (Grant 1977a). This caused significant pressure drawdown in the field (up to 20 bars) and the pressure recovery is still not complete. Good records of production rates, enthalpies and CO_2 contents are available for all the discharging wells (Ministry of Works, 1977) and these were used for testing the models developed here.

LUMPED PARAMETER MODELS

The first model of the Ohaaki zone of the Broadlands geothennal field developed by Grant, 1977a, was a lumped parameter model consisting of a single reservoir block fed by a recharge flow proportional to pressure drop, Using an approximation of the governing mass and energy balance equations to allow easy numerical integration Grant was able to obtain a good match to the pressure history of the field by making suitable choices of the reservoir volume and the recharge coefficient. Further work on lumped parameter models by the present authors and co-workers (Zyvoloski and O'Sullivan, 1978, Krol, 1379 and O'Sullivan et al, 1983) using general-purpose geothermal reservoir simulators confirm the accuracy of Grant's work. With the availability of geothermal reservoir simulators (for example Pruess, 1982 and Zyvoloski and O'Sullivan, 1980) capable of handling gas-rich geothermal fluids setting up a lumped parameter model of the Broadlands field is an easy task. There are basically only two parameters to choose: a storage parameter (porosity if the reservoir volume is taken as known) and a recharge parameter (permeability if a reservoir block and a recharge block are used). Three or four trial simulations enable an excellent fit to the observed pressure decline and recovery to be obtained. However the match to the enthalpy history produced by the lumped parameter models is not satisfactory. Also the lumped parameter model cannot be used for long-term predictions because after a time its behaviour is entirely determined by the recharge assumptions made. For example if the recharge is specified with say an enthalpy of 1300kJ/kg and 4% CO_2 after the time when the total production exceeds the original volume of reservoir fluid then the discharge fluid properties will quickly approach an enthalpy of 1300kJ/kg and 4% CO_2. The lumped parameter model cannot reproduce the changes in reservoir behaviour caused by the spatial variations of fluid properties within the reservoir and the gradual change in recharge fluid properties.

VERTICAL COLUMN MODEL - NATURAL STATE.

To improve on the lumped parameter model of the Broadlands reservoir some spatial variation must be introduced. Also as Grant, 1982, has shown the balance between horizontal and vertical flows is important in determining the behaviour of the Broadlands field. The first model considered in this study consists of a vertical column with lateral recharge. The model used is shown in figure 1. The main reservoir at Broadlands resides in the Waiora and breccia formations. There is also considerable horizontal permeability at the base of the rhyolite but low vertical permeability giving a partial "cap" to the reservoir. The shallow surface layer consists of Huka Falls formation and the basement is ignimbrite.

The first part of the study was a simulation of the natural state of the reservoir. The basic data available for calibrating the model were pressure and temperature profiles (see Sutton and McNabb 1977 and Bixley 1976) and crude estimates of mass flows (see Grant, 1982) to the Ohaaki pool, steam vents and surface discharge. It was possible to obtain a good fit to the pressure profile by taking a vertical permeability in the Wairoa formation and the breccia of 20 millidarcies and a vertical permeability of 5 millidarcies in the rhyolite and 4 millidarcies in the Huka Falls formation. In subsequent production runs it was found necessary to further decrease the vertical permeability at the base of the rhyolite (see later) but this variation has a minor effect on the vertical pressure distribution. The total throughflow for the system was set at 15 kg/s (somewhat arbitrary). The same pressure profile could be obtained for an increased flow rate by using a corresponding increase in vertical permeability everywhere. The enthalpy of the fluid injected at the base of the model was then varied to give a good match to the observed temperature distribution, The best fit enthalpy value used here was 1340kJ/kg. The CO_2 content of the injected fluid was set at 4% as suggested by Sutton and McNabb, 1977. This produces partial pressures of CO_2 in the range 0.5 - 1.7MPa in the reservoir which are compatible with estimates given by Grant, 1977b.

The flow to the Ohaaki pool and steam vents were both modelled as pressure dependent well discharges in the form

$$q = C \cdot (p - p_{crit}).$$

The "critical" pressure in this formula, p_{crit}, is the pressure at which the discharge ceases. It was taken as 80% of the initial pressure for the Ohaaki pool and 0.025MPa below the initial value for the steam vents. These figures fit in roughly with the observed stopping of the flow to the Ohaaki pool and the drying up of the steam vents. The "deliverability" coefficients C were adjusted to give approximately 7 kg/s flow to the Ohaaki pool and 2kg/s to the steam vents. For the Ohaaki pool "well" the discharge enthalpy was taken as the flowing enthalpy for the conditions in the source block whereas for the steam vents only vapour is discharged. In all the simulations reported here a weighted combination of 90% of the Core relative permeabilities and 10% of the X-relative permeabilities was used.

Similar results are obtained if the X-relative permeabilities alone are used (see O'Sullivan et al, 1983).

The results shown in figures 2,3,4 and 5 are for the reservoir parameters shown in table 1. Here the basic parameters are modified somewhat to give a better exploitation performance of the model. In particular the permeability at the base of the rhyolite is reduced to 1.0 millidarcy and the permeability at the top of the Waiora formation is reduced to 3.0 millidarcies.

Comparisons between calculated and observed pressure and temperature profiles are shown in Figures 2 and 3, respectively. The agreement is good. Figure 4 shows the calculated vapour saturation and Figure 5 the profile of partial pressure of CO_2. The partial pressure of CO_2 in the main reservoir is 0.5 - 1.7 MPa. The vapour-saturation profile shows very low values in the main reservoir region (close to the residual vapour saturation of 0.05). The vapour-saturation profile in the rhyolite and Huka Falls formation reflects the combination of two effects: rather high vapour saturations are necessary to enable the required through-flow of CO_2, and the low vapour saturation at a depth of 300 m is a result of the gas escaping to surface manifestations (Ohaaki Pool and steam vents.)

EXPLOITATION STUDIES

The best-fit steady-state pressure, temperature, and CO_2 distribution were then used as initial condftions for simulations of the exploitation and recovery of the Ohaaki reservoir during 1968-1974. In the exploitation model, a pressure dependent recharge was allowed in each of the reservoir blocks. The enthalpy and CO_2 content of the recharge to each block is maintained constant at its initial value.

For this vertical-column model the production data used for the single-block model was classified as either deep or shallow, using information on feed zones given by Grant, 1980. The deep production was assigned to block 9 (BR 9, 13, 17-23, 25), the shallow production to block 6 (BR 2, 3, 8, 11). In calibrating the model, the parameters which can be varied without any change to the intitial steady-state model are the porosity of each block and the recharge coefficient for each reservoir block. Two general cases were considered. In Case I the porosity and recharge coefficients in the production zone (blocks 6, 7, 8, 9) were assumed to be uniform. In Case II, the porosity and recharge coefficients were allowed to be different in block 6 from those in block 7, 8 and 9. The nonuniformity of recharge coefficients in Case II allows the high-permeability zone at the contact between the rhyolite and the Waiora formation to be represented.

In both Case I and Case 11, the porosities and recharge coefficients were then adjusted to give a good match to the pressure response. Then the pressure in block 9 , in the lower production block, was used as the reservoir pressure to compare with recorded data (see Hitchcock and Bixley, 1975). By running a few simulations, it was possible to obtain a very good pressure match. The most interesting results from the model, however, are the production enthalpy data. For Case I (uniform recharge coefficient), the production enthalpy was much too high from the shallow wells and too low from the deep wells. However, for Case II, the much higher recharge coefficient in block 6 lowered the production enthalpy from the shallow wells and the lower recharge coefficient in block 9 increased the production enthalpy from the deep wells. These results confirm the postulated high horizontal permeability just below the rhyolite (see Grant, 1982).

Another modification to the model was required to produce a good match to the early enthalpy rise, namely a low vertical permeability in the neighbourhood of the upper feed zone (see table 1). The pressure history for this version of the model is compared with the observed pressure decline in figure 6. The production enthalpy histories and CO_2 content histories shown in figures 7, 8, 9 and 10 respectively compare the "best-fit" results with those for different permeabilities at the base of the rhyolite.

SUMMARY

The vertical column model considered here can give a much better fit to the observed discharge enthalpy than a simple lumped parameter. The model could be improved by locating the feed points of the individual wells more carefully. Also some of the data used in calibrating the model, such as the discharge rates to the Ohaaki Pool and surface steam vents, have not been carefully checked and should be improved.

However the model is basically limited by its approximation of horizontal flow as a pressure dependent recharge, with constant enthalpy and CO_2 content. For any long-term simulation study some realistic spatial variation in the horizontal direction as well as the vertical direction is required.

The present model is very useful for gaining information about the vertical permeability distribution at Broadlands. It is successful in representing the vertical temperature and pressure distribution in the reservoir as well as producing a good match to the relatively short-term 1966-74 exploitation history.

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FIGURE 1

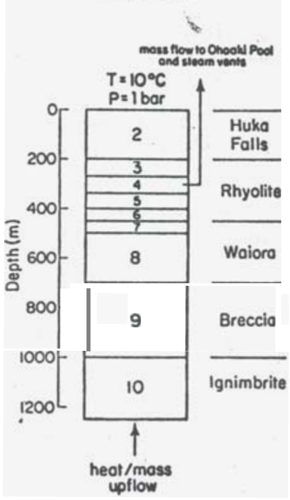

Table 1. Model Parameters

Block	k(md)	ø
2	4	0.20
3	5	0.15
4	5	0.15
5	1	0.15
6	3	0.12
7	20	0.12
8	20	0.12
9	20	0.12
10	1	0.10

Thermal conductivity: 1.7 W/m.°C
Rock density: 2500 kg/m³
Heat capacity: 900 J/kg.°C
Cross sectional area: 1.0 km²

Heat/mass upflow

Total mass: 14.77 kg/s
Mass CO_2 : 0.59 kg/s
Heat: 19.79 MW

Mass flow to surface springs

Ohaaki pool: 7.20 kg/s
Steam vents: 2.37 kg/s

FIGURE 2
STEADY STATE PRESSURE PROFILE

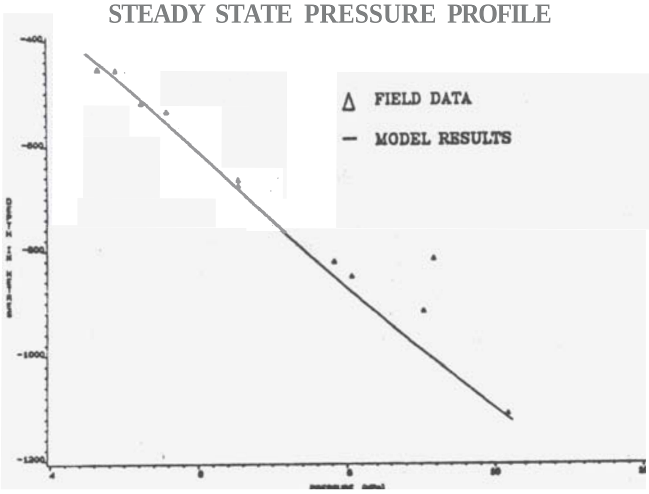

FIGURE 3
STEADY STATE TEMPERATURE PROFILE

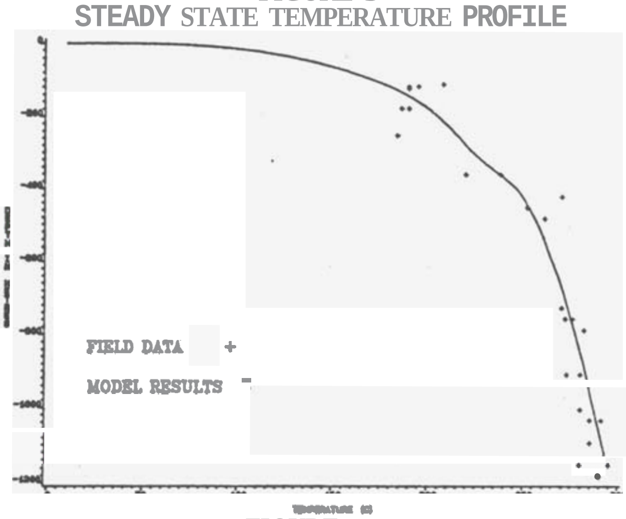

FIGURE 4
STEADY STATE SATURATION PROFILE

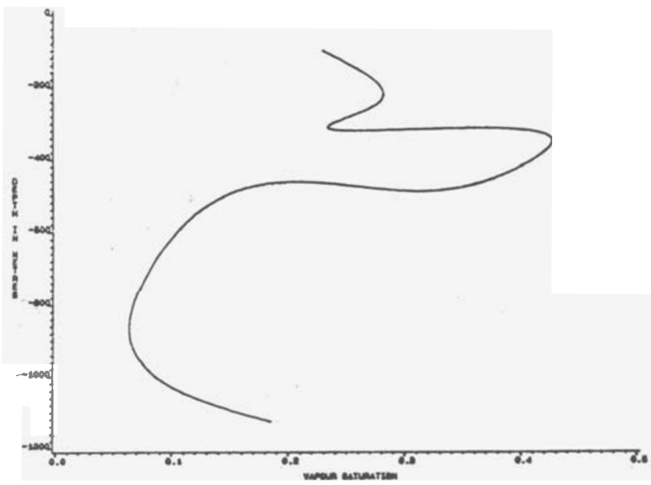

FIGURE 5
STEADY STATE PARTIAL PRESSURE

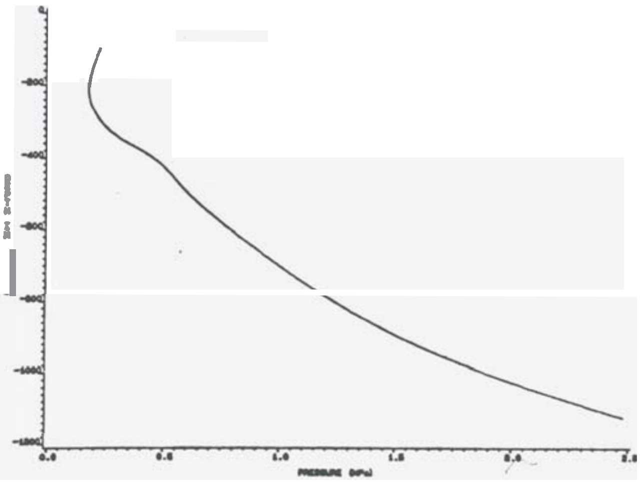

FIGURE 6
PRESSURE DECLINE AT OHAAKI

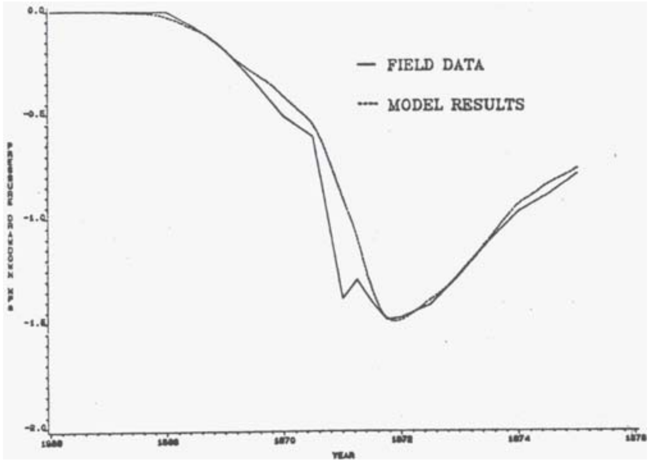

FIGURE 7
DISCHARGE ENTHALPY IN UPPER RESERVOIR

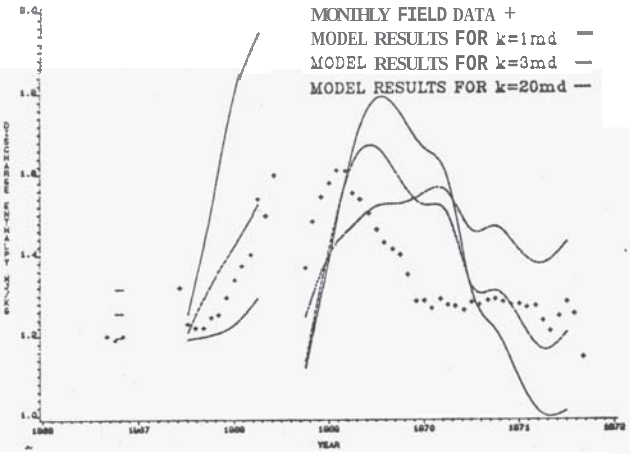

FIGURE 9
C02 IN DISCHARGE FROM UPPER RESERVOIR

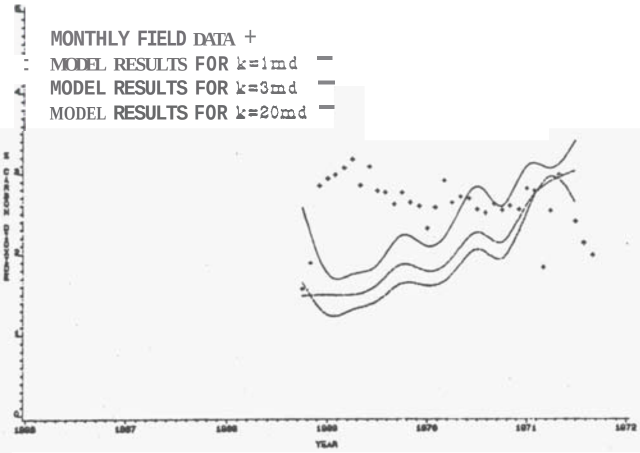

FIGURE 8
DISCHARGE ENTHALPY IN LOWER RESERVOIR

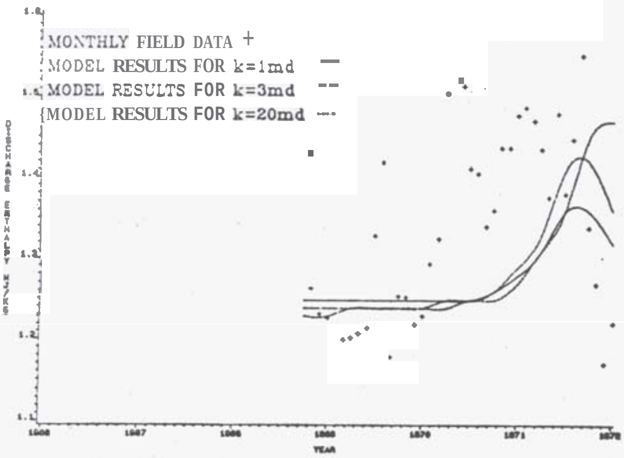

FIGURE 10
C02 IN DISCHARGE FROM LOWER RESERVOIR