

OPTIMIZED NUMERICAL MODELING OF PRODUCTION FROM THE POIHIPI DRY STEAM ZONE: WAIRAKEI GEOTHERMAL SYSTEM

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ABSTRACT

The Poihipi power station utilizes dry steam from a shallow zone near the margin of the Wairakei geothermal reservoir. The station has an installed capacity of 55 MWe, however resource consents limit the average daily production to approximately 25 MWe. The plant has been operated for several years with daily variations in the production rate. The corresponding pressure history provides a good database for testing models of the reservoir.

In the first stage of modeling, a model for each well was set up, assuming that the reservoir is a single layer and that the flow near a well is approximately radially symmetric. Three different types of model (uniform porous medium, fractured medium and fractional dimension) were calibrated using data from a three day period. The best match to the pressure data was achieved with the fractional dimension model with a dimension of approximately 2.5 (i.e. midway between 2D and 3D flow).

Then the fractional dimension models were embedded into a 2D reservoir model including all the wells and some of the surrounding area. The new composite model was calibrated with production history for a seventy-six day period. This composite small-scale reservoir model should be useful for making medium term predictions.

1. INTRODUCTION

The Wairakei geothermal system is located at the south eastern margin of the Taupo Volcanic Zone (Figure 1). It is a liquid-dominated system with production-induced dry zones in parts of the TeMihi area and the nearby Poihipi Road area. The Poihipi power station is situated on the north western margin of the Wairakei geothermal system (Figures 2 and 3). It has an installed capacity of 55 MWe from a single condensing turbine unit. The power station utilizes

dry steam from shallow wells, located close to the north-western edge of the resistivity boundary of the Wairakei/Tauhara system (Figures 2 and 3).

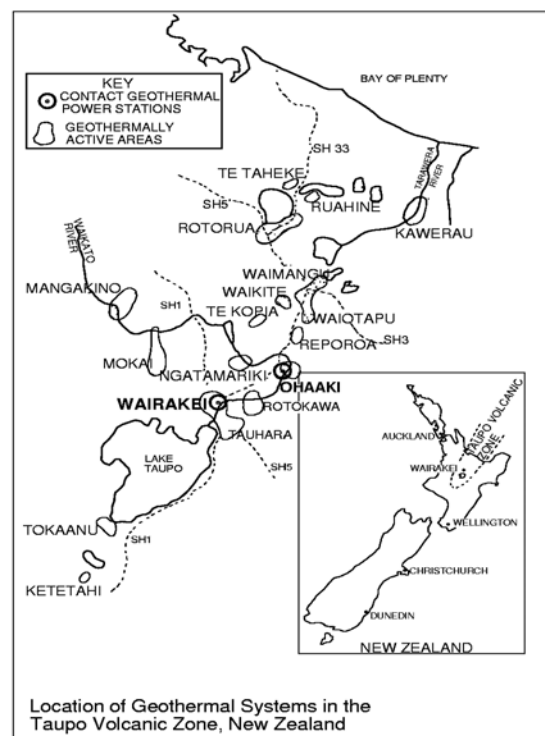


Figure 1. Map of the TVZ and the location of Wairakei geothermal system.

The steam condensate (~ 70 tonnes/hour) at 20 °C is injected into one well which is located further to the west outside the resistivity boundary, about 2.5 km from the nearest production well (Figure 3). WK613 and WK620 are the closest monitoring wells (Figure 3) and they are continuously logged to monitor changes in reservoir pressures. A portion of the produced steam is used to supply the Geotherm Exports glasshouse.

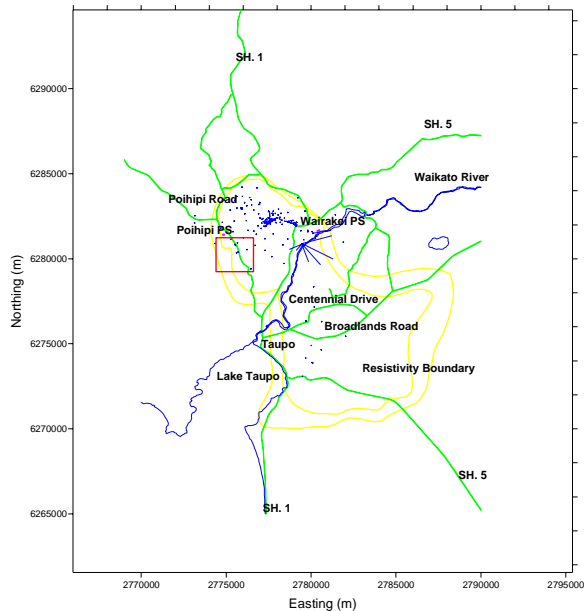


Figure 2. The Wairakei-Tauhara system with the Poihipi area shown in Fig. 3 outlined in red.

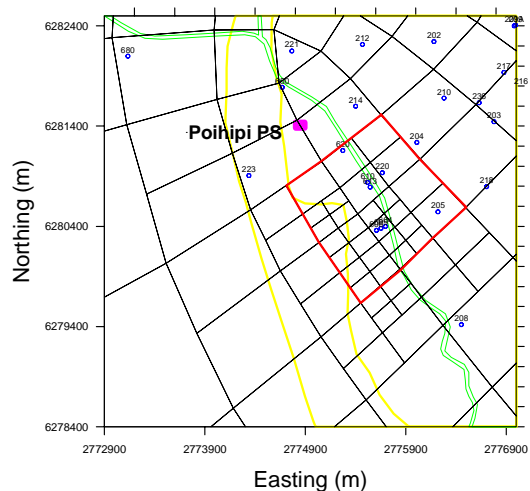


Figure 3. The area surrounding the Poihipi power station (PS) showing the position of production, reinjection and monitoring wells. The boundary of the 2D model discussed below is shown in red.

The steam intake to the Poihipi power station is limited to 200 tonnes/hour by the current resource consent. This limited steam supply to the power station has prompted a cyclic operation mode (Figure 4). The power station is currently producing a daily average of ~ 25 MWe which is about 45 % of its design generation capacity.

The steam chemistry of the Poihipi wells shows little change since the start of production in 1998 with weight percentage of gas in the steam relatively constant in all wells. This indicates that there is no

depletion or dilution of the low gas steam and no evidence of significant meteoric water input (Mannington et al., 2004a).

Previous modeling studies of the Wairakei-Tauhara reservoir (Mannington et al., 2004b) have used only average production values, rather than the detailed production history of the Poihipi wells.

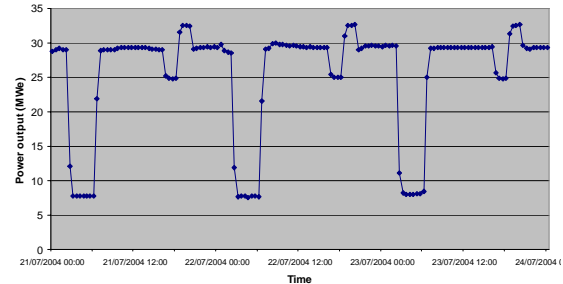


Figure 4. Power output (MWe) for the Poihipi power station during three days of normal operation.

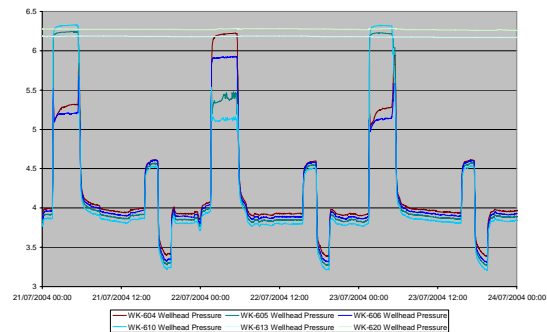


Figure 5. WHP (barg) for the Poihipi production wells, WK604, WK605, WK606 and WK610), and two monitoring wells (WK620 and WK613).

2. OBJECTIVES

The cyclic operation of the Poihipi production wells (Figure 4) and the resulting cyclic pressure response (Figure 5) provides an excellent data set with which to test and calibrate a reservoir model. The aim of the present work is to develop a small scale model that can match this detailed production history. A sequential approach is adopted: first the behaviour of each well is modelled separately, and secondly a more extensive model is set up covering a large enough area to include all the production wells and observation wells. The isolated well models use one-dimensional radial grids. For the second, larger scale model, a composite grid is used consisting of a single layer two-dimensional grid with a radial one-dimensional grid embedded around each production well.

For the radial-grid isolated well models, three different types of model were investigated:

1. Uniform single layered porous media model.
2. A double porosity fracture/matrix model.
3. Fractional dimension model.

The calibration of each type of model to achieve a best fit with the data was carried out with the automated well-test analysis system (AWTAS) developed at the University of Auckland (O'Sullivan et al., 2005). The model that gave the best match with measured data was then used as the embedded grid part of the two-dimensional reservoir model of the whole Poihipi region. The two-dimensional composite grid model is implemented with the TOUGH2 simulator.

Thus there are two major objectives with this study:

- (i) To produce a small scale reservoir model that is able to provide short- to medium-term predictions about the behaviour of the Poihipi wells.
- (ii) To establish a composite grid methodology, based on the embedding of suitable radial one-dimensional grids into the small-scale reservoir model, that will enable the model to be used both for short-term and medium-term modelling.

3. PERMEABILITY STRUCTURE

From the stratigraphy and completion reports of the wells in the Poihipi area, it is evident that production is fed from the permeable Waiora formation that extends horizontally at an average depth of 358 mRL and has an average thickness of 125 m in this part of the Wairakei system. Taking account of the permeable contact zones with the overlying Huka falls formations and the underlying Karapiti Ila Rhyolite, it is reasonable to use a reservoir thickness of 150 m for steam production in the Poihipi area.

4. WELLSIM MODELING

The available transient pressure data (Figure 5) are measured at the wellhead (WHP). In order to calculate the corresponding flowing reservoir pressures for each well, the wellbore simulator WELLSIM (Murray and Gunn, 1993) was used for a back calculation taking account of pressure drops due to friction, acceleration and gravity. For each well, assuming steady conditions, five values of WHP and the corresponding mass flow rates were used in WELLSIM and the reservoir pressures were calculated. The difference between the reservoir pressure and the WHP was fitted using a linear function for the lower range of mass flow rates and a quadratic for the upper range of mass flow rates. The pressure difference functions (see results for WK606

in Figure 6) were then used to convert all values of WHP into the corresponding reservoir pressure.

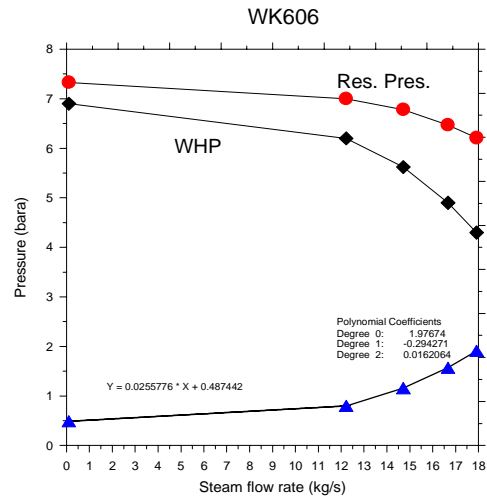


Figure 6. WELLSIM results for conversion of WHP to reservoir pressure for WK606.

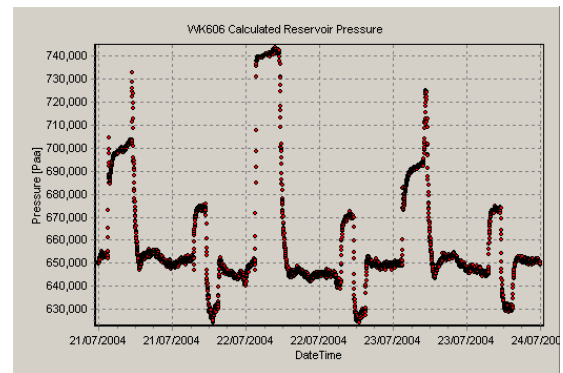


Figure 7. Calculated reservoir pressures for WK606 corrected for atmospheric pressure and for pressure drop in the well.

The results for WK606 are shown in Figure 7. The same procedure was carried out for all wells to convert the WHP into reservoir pressure. The interference between the production wells and the monitoring wells is not significant, as the pressure drop is less than the measurement error of 0.1 bar. Therefore the monitoring data were not used in the current modeling study.

5. RADIAL RESERVOIR MODELS (AWTAS)

Radial models with a thickness of 150m and an effectively infinite outer radius were used to model the behaviour of each production well. The Automated Well-Test Analysis System (AWTAS) software (O'Sullivan et al., 2005) was used to calibrate the models, i.e. to achieve the optimal match of the model output with the corrected reservoir data (Figure 7). AWTAS uses a number of fast and very

robust numerical solvers, all of which are based on the integrated finite difference formulation used in TOUGH2 (Pruess, 1991, 1997, Pruess et al., 1999).

During the fitting process the model simulation is run many times with different input parameters adjusted by the optimisation algorithm in AWTAS. Because of the high accuracy of the production data at Poihipi, measurement errors of 0.1 kg/sec for mass flow rates and 5000 Pa for pressures were specified for the AWTAS simulations.

Two sets of input parameters are used for the calibration of models. The first set consists of fixed parameters whose values are relatively well defined and which do not greatly affect the model performance (Table 1). The second set of parameters consists of the variable parameters optimised by AWTAS. For the simple homogeneous porous medium model the variable parameters are permeability and porosity. For the other models there are some additional variable parameters (discussed below).

Property	Value
Rock specific heat	1000 J/kg K
Rock thermal conductivity	2.25 W/m K
Rock density	2500 kg/m ³
Rock compressibility	1.0E-10Pa ⁻¹
Steam saturation	0.3
Relative permeability (Corey curves)	$S_{fr} = 0.55$ $S_{fv} = 0.45$

Table 1. Fixed parameters used in AWTAS (mostly taken from the full-scale Wairakei model).

5.1 Homogeneous Porous Medium

This model assumes that the reservoir layer consists of a homogenous porous medium throughout, with the same permeability and porosity assigned to all model blocks. Thus the model has two variable parameters (permeability and porosity), which are varied to maximize agreement between model results and field data.

The match obtained is reasonable in general (Figure 8), but the model results are unsatisfactory in two respects:

- There is a long-term decline which is not present in the data.
- Neither the pressure increase after shut-in nor the pressure decrease after production recommences are rapid enough.

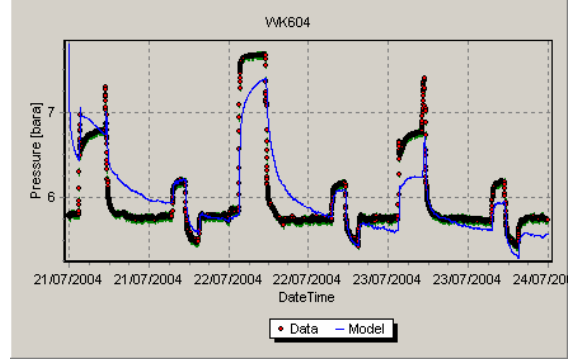


Figure 8. AWTAS optimized modeling results for a single layer uniform porous media for WK604.

5.2 Double porosity Fracture/Matrix model

In this type of model the flow from the reservoir to the well is treated as horizontal flow through a fracture zone with vertical flow in and out of an adjacent low permeability matrix. This model is similar to the MINC model used for modelling fractured geothermal reservoirs (Pruess and Narasimhan, 1985). We have considered one highly permeable fractured layer sandwiched between two matrix layers with lower permeability and porosity. A reasonable match between the model performance and the measured data can be obtained for a range of fracture apertures. We have chosen to use a relatively large 2 m fracture aperture since it fits the fault scarp size.

For this model there are four parameters: the porosities and permeabilities of the fracture and the matrix. Experiments with AWTAS showed that it was possible to obtain more than one solution for the best-fit model depending on the initial guesses for the porosities and permeabilities. Evidently the 4-dimensional surface representing the objective function is fairly flat and has local minima. Further sensitivity analyses showed that the model behaviour is more sensitive to changes in permeabilities (of fracture and matrix) than to changes in the porosities.

To investigate the best-fit parameters further, a grid search with fixed porosity values but variable fracture and matrix permeabilities was carried out. A typical plot of the results is shown in Figure 9.

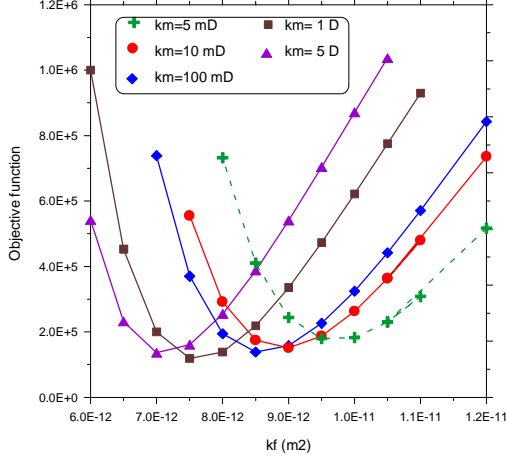


Figure 9. Grid search results for various permeabilities

Well	ϕ_m	$k_m \text{ m}^2$	ϕ_f	$k_f \text{ m}^2$
WK604	0.20	2.00E-14	0.27	2.47E-11
WK605	0.20	1.13E-15	0.29	3.68E-11
WK606	0.16	8.12E-15	0.23	6.04E-11
WK610	0.20	5.00E-15	0.30	2.48E-11

Table 2. Best-fit parameters for the fracture/matrix model

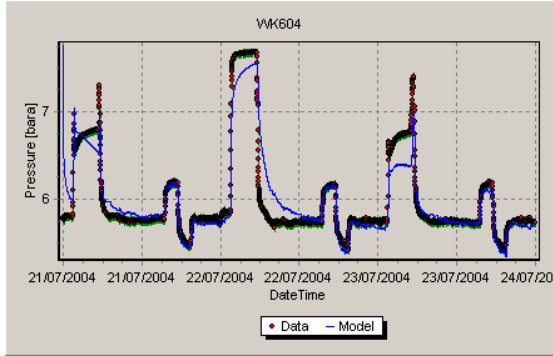


Figure 10. AWTAS optimized modeling results for multi layered porous media with a single 2m fracture in the middle for WK604.

It was decided after this investigation that the matrix permeability should be restricted to the interval 1-10 mD. AWTAS was re-run with this constraint. The best-fit parameter values are given in Table 2 and a typical best-fit result is shown in Figure 10.

5.3 Fractional Dimension (fractal) Modeling

It has been suggested by some authors that a fractured reservoir can be represented by a “fractional

dimension” model (O’Sullivan et al., 2005). The homogenous porous layer model of section 4.1 represents a two dimensional model. In some cases the fractured network feeding a well may have a geometric structure that is somewhere between two and three dimensional. This can be represented by a fractional dimension system where the volume swept out by the fracture system, and the area enclosing it, increases with the radial distance from the wellbore at an intermediate rate (between those for a 2D and a 3D model).

The fractional dimension model takes a continuum approach to representing the fractures rather than modeling them explicitly. This is done by simply modifying the specifications of block volumes and interface areas of the homogeneous porous layer model, according to the equations below:

$$V_i = (\alpha_n b^{3-n} / n) (r_{i+1/2}^n - r_{i-1/2}^n) \quad (1)$$

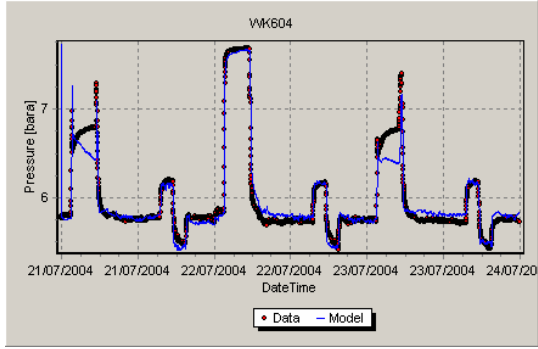
$$A_{i+1/2} = \alpha_n b^{3-n} r_{i+1/2}^{n-1} \quad (2)$$

$$\alpha_n = \frac{2\pi^{n/2}}{\Gamma(n/2)} \quad (3)$$

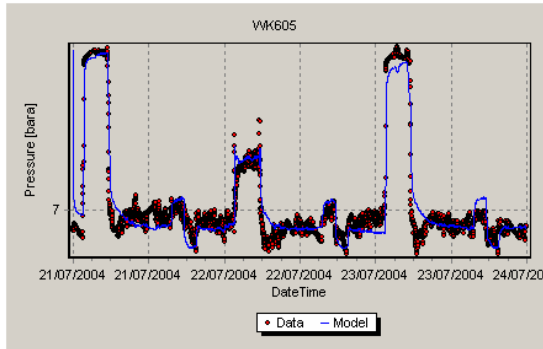
Here n is the dimension of the model, Γ is the Gamma function, V_i is the volume of the i th block located between radii r_{i-1} and r_i , $A_{i+1/2}$ is the interface area located between the i^{th} and $(i+1)^{\text{st}}$ blocks at a radius of $r_{i+1/2}$, and b is the layer thickness. For the special cases of 1D, 2D and 3D (i.e. $n = 1, 2$ or 3) the volumes and interface areas are shown in the Table 3.

Dimension of model	V_i	$A_{i+1/2}$
1 (Column)	$2b^2(r_{i+1/2} - r_{i-1/2})$	$2b^2$
2 (Cylindrical)	$\pi b(r_{i+1/2}^2 - r_{i-1/2}^2)$	$2\pi b r_{i+1/2}$
3 (Spherical)	$(4\pi/3)(r_{i+1/2}^3 - r_{i-1/2}^3)$	$4\pi r_{i+1/2}^2$

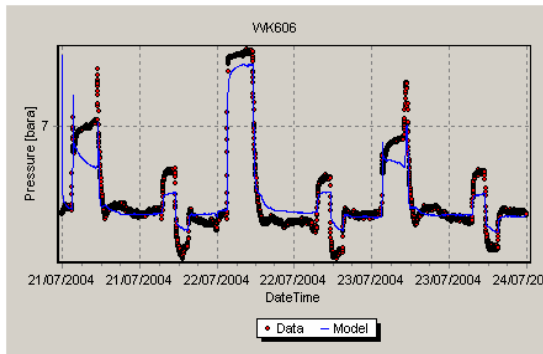
Table 3. Volumes and interface areas for the fractional dimension model (special cases).



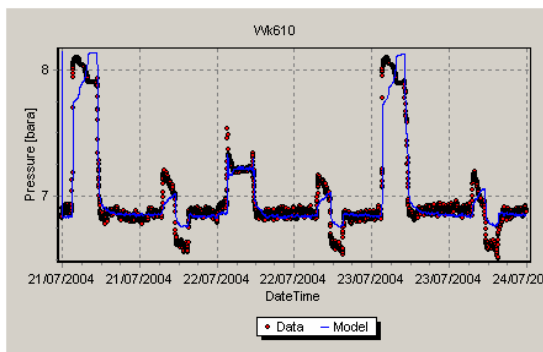
(a) WK604



(b) WK605



(b) WK605



(d) WK610

Figure 11. AWTAS optimized modeling results for the fractional dimension model.

The fractional dimension model gave an excellent match with measured data (see Figure 11).

The parameter values obtained from the optimized models are shown in Table 4. It is interesting to note that the dimension is close to 2.5 in all cases and that a large permeability is required.

Well	Porosity	Permeability (m ²)	Fractional dimension
WK604	0.30	2.95E-12	2.589
WK605	0.30	4.24E-12	2.4
WK606	0.30	3.52E-12	2.45
WK610	0.30	4.37E-12	2.704

Table 4. AWTAS optimized fractional dimension model parameters, data for three days.

5.4 Long term data

The best models obtained from the well-by-well matching procedure were then tested on some longer-term data, measured over seventy-six days. It was found that the model fit was unsatisfactory for the whole seventy-six days and AWTAS was used to recalibrate all the models. The parameter values obtained from the models optimized over seventy-six days are shown in Table 5.

Well	Porosity	Permeability (m ²)	Fractional dimension
WK604	0.30	3.00E-12	2.593
WK605	0.30	5.20E-12	2.45
WK606	0.30	2.92E-12	2.408
WK610	0.30	5.70E-12	2.75

Table 5. AWTAS optimized fractional dimension model parameters, data for 76 days.

The parameter values are similar to but not identical with those given in Table 4. A typical result for WK604 is shown in Figure 12.

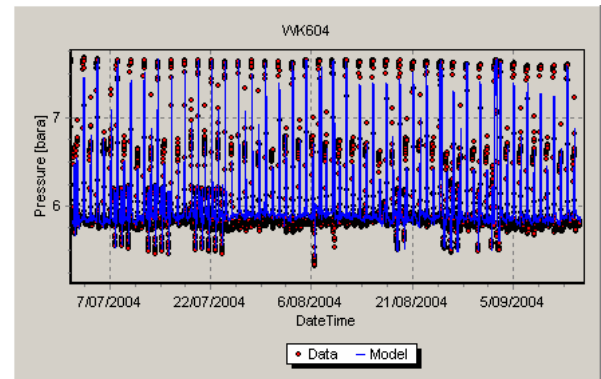


Figure 12. AWTAS optimized modeling results for the fractional dimension model, using data for 76 days (WK604).

6. SMALL-SCALE RESERVOIR MODEL

The small-scale reservoir model including the four production wells was set up (Figure 13). The basic model was set up as a single layer with a thickness of 150 m. Within this model an embedded radial grid (not shown) from the fractional dimension model was used inside each production block. This technique is commonly used in oil reservoir modeling.

The total volume of the embedded radial blocks occupies a maximum of about 25% of the original volume of the block. This allows for more accurate representation of the near-well behaviour, while keeping a normal model structure, with the larger blocks, to represent wider-scale effects.

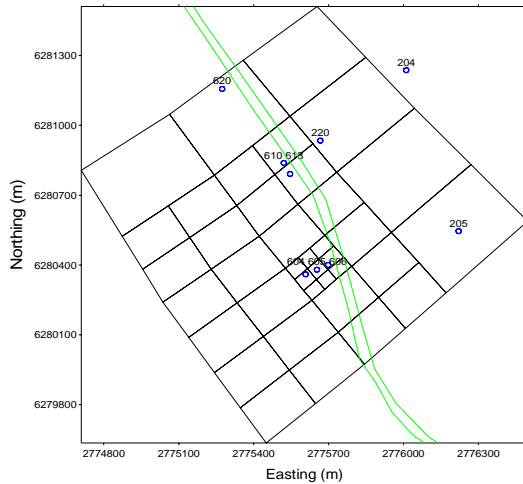


Figure 13. The area chosen from the Wairakei grid (Figure 3) for the small-scale Poihipi model.

At first the optimized parameters from Table 5 were used for the embedded sub-grids and some trial and error runs were used to select an optimum background permeability, assumed to be constant throughout the model. This process gave a fit to the data that was not as good as that shown, for example, in Figure 12. This is a result of interaction between the different production wells. Some further recalibration was carried out, adjusting the permeabilities in the embedded sub-grids. The final permeabilities used are shown in Table 6.

The model gave a very good match between model results and data for the short term run (Figure 14) and long term data (Figure 15). A zoom-in of Figure 15 is given in Figure 16. The early mismatch between measured data and modeling results is clear in Figure 15 and can be related to the reservoir model starting from a high reservoir pressure of 7.9 bar abs., while

the measured data are simply a continuation of the previous production history.

Well	Porosity	Permeability (m ²)	Fractional dimension
WK604	0.30	3.00E-12	2.593
WK605	0.30	5.20E-12	2.45
WK606	0.30	2.92E-12	2.408
WK610	0.30	5.70E-12	2.75
Background	0.30	4.00E-12	-----

Table 6. Optimized model parameters for the 1D/2D composite model, using data for seventy-six days.

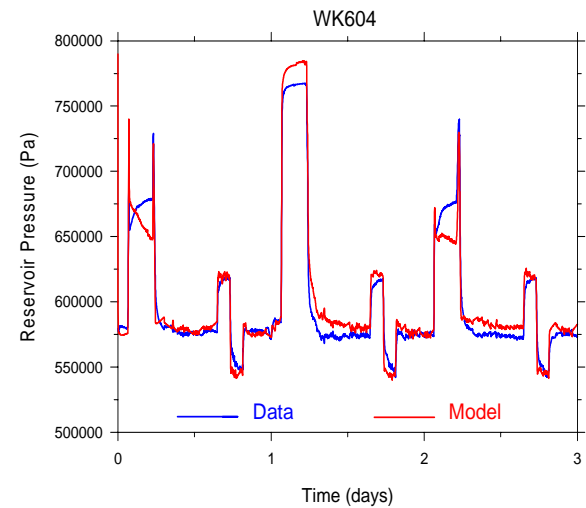


Figure 14. Short term modeling result using the small-scale Poihipi model of Figure 13.

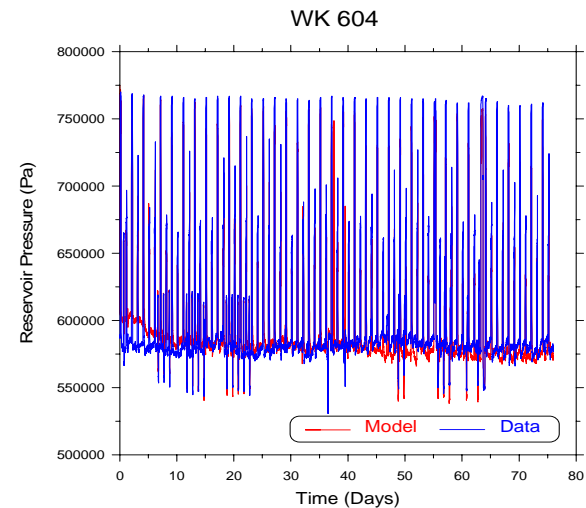


Figure 15. Long term modeling result using the small-scale Poihipi model of Figure 13.

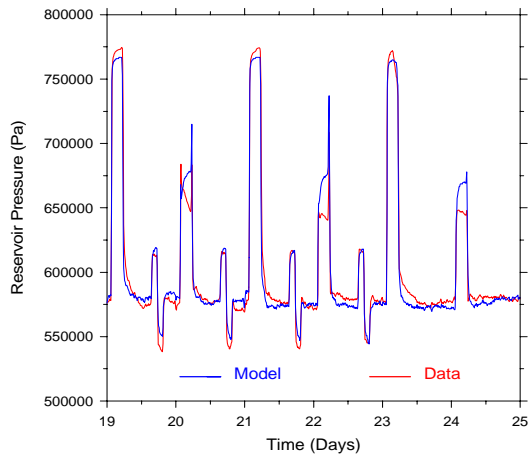


Figure 16. A zoom-in on part of Figure 15.

7. CONCLUSION

The single-layer porous medium model gave the worst fit to the data. Clearly the flow near the Poihipi wells is not approximately 2D. There is a significant vertical component. Both the multi-layer fracture/matrix model and the fractional dimension model give much better results. The fractional dimension model gives the best match with the long-term field data, and the flow in the single layered reservoir is definitely not two dimensional ($3 > n > 2$).

An advantage of using the fractional dimension model is that it has a simple 1D block structure, whereas the multi-layer fracture/matrix model requires an increase in the number of blocks in the model and cannot be simply embedded into a larger reservoir model.

The next stage of the research will use the composite 2D grid model to investigate a longer production history and to model the long term response of the reservoir to production, especially recovery after extended shutdowns.

8. ACKNOWLEDGMENT

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9. REFERENCES

- Mannington, W., Mroczek E. and Roberts K. (2004a) Wairakei Geothermal Field, 2003 Annual report of reservoir and scientific monitoring.
- Mannington, W. O'Sullivan, M. and Bullivant, D. (2004b) Computer modelling of the Wairakei-

Tauhara geothermal system, New Zealand. *Geothermics*, **33**, 401-419.

Murray, L. and Gunn, C. (1993) Toward integrated geothermal reservoir and wellbore simulation: TETRAD and WELLSIM. *Proceedings of the 15th New Zealand Geothermal Workshop*, 279-284.

O'Sullivan, M. J. (2004) Evidence of Michael John O'Sullivan. IN THE MATTER an application by CONTACT ENERGY LIMITED for resource consents for the Wairakei Geothermal Power Plant.

O'Sullivan, M. J., Croucher, A. E., Anderson, E. B., Kikuchi, T. and Nakagome, O. (2005) An Automated Well-Test Analysis System (AWTAS), *Geothermics*, **34**, 3-25.

Pruess, K. (1991) TOUGH2 – A general-purpose numerical simulator for multiphase fluid and heat flow, Report LBL-29400, Lawrence Berkeley Laboratory, Berkeley, CA.

Pruess, K. (1997) TOUGH2 – An Update, Proceedings 19th New Zealand Geothermal Workshop, University of Auckland, 211-216.

Pruess, K., and Narasimhan, T.N. (1985) A Practical Method for Modeling Fluid and Heat Flow in Fractured Porous Media, *Society of Petroleum Engineers Journal*, **25** (1), 14-26.

Pruess, K., Oldenburg, C. and Moridis, G. (1999) TOUGH2 User's Guide, Version 2.0, Report LBNL-43134, Lawrence Berkeley National Laboratory, Berkeley, CA.