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Modelling reinjection into vapour-dominated two-phase systems: Part 1—Experiments on model design

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ABSTRACT

Water injection into vapour dominated geothermal systems has been recognized as a necessary strategy to sustain production of geothermal resources. Computer simulation is an important tool in the planning and management of injection. Because of enhanced techniques and their flexibility, geothermal simulators can make a range of approaches to simulate this process; however different settings of a model may lead to different predictions. In order to progress to a good generic 3D model which can produce a realistic prediction of injection effects in vapour-dominated two-phase reservoirs, we decided to first set up a 2D model which allows numerical experiments to be carried out quickly. This 2D model was used to investigate the effect of different model parameters on the predictions of performance and to assess the importance of various modifications to the model. The aim of these experiments was to determine the best choice of model parameters to obtain a model of a vapour-dominated reservoir suitable for the investigation of reinjection effects.

The model is based loosely on the Darajat system but the results should be relevant for other similar reservoirs such as Larderello, Kamojang and The Geysers. Model parameters such as vertical permeability, porosity and relative permeability are investigated. Different injection rates and start-times for injection are tried. Various aspects of model design such as grid refinement, use of an embedded radial grid near the wells, dual porosity and nine-point differencing are investigated.

1. Introduction

Vapour-dominated two-phase systems produce dry steam but they contain a large amount of immobile water. Within their reservoir zone there are high temperatures (250–330 °C) and comparatively low pressures. These systems have low permeability in the reservoir zone and very low permeability surrounding the reservoir. Hence natural recharge is very limited from the surrounding rocks. As the pressure decreases in this type of geothermal system during production, more and more of the immobile water boils to form steam which then flows towards the production wells. Since the water in a vapour-dominated reservoir is not replenished by natural recharge and, after some years of production, parts of the reservoir may run out of immobile water and become superheated (i.e., the pressure of the steam drops below the boiling point).

In this paper the Darajat geothermal field is chosen as a case study for two reasons: first it is a typical vapour-dominated geothermal system (Alamsyah et al., 2005; Hadi et al., 2005) and secondly an existing computer model of Darajat was available at the University of Auckland. The Darajat model has a three dimensional, regular, rectangular grid structure. It was used to represent the natural state and production history of Darajat field.

Injection into vapour-dominated reservoirs involves complex fluid flow and heat transfer processes including boiling and condensation with strong latent heat effects. Also there is vapour-liquid counter-flow with steam rising and water trickling down. The TOUGH2 geothermal reservoir simulator (Pruess et al., 1999) can model these physical processes, including the highly non-linear phase transitions from vapor to two-phase, and then to all- liquid conditions and the associated strongly coupled fluid flow and heat transfer effects. However, this capability for simulating the basic processes does not necessarily guarantee realistic predictions for practical injection problems that involve multidimensional flow effects on a broad range of space and time scales (Pruess, 1991). Therefore to obtain accurate and realistic predictions for modelling injection into vapour-dominated reservoirs, the reservoir parameters and various aspects of model design need to be investigated in detail.

Experiences with modelling vapour-dominated reservoir reported in the literature show that different versions of a model may lead to different predictions, mainly because of discretization

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effects, lack of information about relative permeabilities, grid orientation and reservoir heterogeneity.

For example Schroeder et al. (1982) tried various grid spacing on a 1D radial model. Their study shows that models with different sizes of grid blocks produce results with oscillations of different frequency and amplitude. Additionally by trying different relative permeabilities, they showed that the behaviour of their model was strongly affected by the choice of relative permeabilities. Pruess (1994) and Fitzgerald et al. (1994) showed the sensitivity of the predictions of numerical models to grid orientation and the accuracy of the finite difference scheme. Therefore it is not easy to set up a good model which produces a realistic prediction of injection effects in vapour-dominated two-phase reservoirs. The aim of the present study is to carry out sensitivity studies on a simple 2D model of a vapour dominated geothermal reservoir to investigate the effect of different model parameters on the predictions of performance and to assess the importance of various modifications to the model. These experiments were used to determine the best choice of model parameters to obtain a model of a vapour-dominated reservoir suitable for the investigation of reinjection effects. This paper was intended as a pre-cursor to a subsequent study on a similar approach with a 3D model (Kaya, 2016).

The simulations were carried out with AUTOUGH2 (Yeh et al., 2011, 2012, 2013), the University of Auckland's version of TOUGH2, and MULgraph (O'Sullivan and Bullivant, 1995) was the main visualisation tools used in this study.

2. Model description

In order to carry out a large number of numerical experiments very quickly, first a 2D model was set up. It is based on a typical vertical slice through the Darajat Model and is 10 km long, 4.8 km deep and consists of 17 layers. The outer zone rock has a very low permeability (0.04–0.16E − 15 m^2) to prevent cool water flooding the vapour-dominated zone. Similarly a low permeability cap-rock is assigned to the top of the reservoir.

The atmospheric conditions maintained at the ground surface are 1 bar pressure and 15 °C temperature. As shown by the modelling studies of O'sullivan (1990), it is not possible to produce a stable steady state vapour-dominated system by applying a constant mass and energy flow at the base of the model. By considering the stability of a 1-D heat pipe (counter-flow of liquid and steam driven by gravity in a uniform porous medium) McGuinness et al. (1993) showed that a vapour-dominated reservoir has saturation control at depth. Therefore in the 2D model constant pressure and saturation boundary conditions (126 bar pressure and 0.25 vapour saturation) are applied at the base of the reservoir blocks. At the base of the model outside the reservoir a 0.06 W/m^2 heat input is applied as the basement boundary condition.

To represent flow from the hot springs a deliverability model is used. For the deliverability option wells produce against a prescribed flowing bottom-hole pressure, p_{wb}, with a productivity index PI (Pruess et al., 1999). The mass production rate of phase β from a grid block with phase pressure $p\beta > p_{\mathrm{wb}}$ is given by;

$$q_\beta = \frac{k_{r\beta}}{\mu_\beta}\rho_\beta \mathrm{PI}(p_\beta - p_{wb}) \tag{1}$$

here q is mass flux (kg/m^{2}s), k_{r} is relative permeability for phase β (m^2), μ is dynamic viscosity (*kg/m.s*), ρ is density (kg/m^3), PI is productivity index m^3, p is fluid pressure and p_{wb} is the bottom-hole wellbore pressure (Pa).

Table 1
Rock-types and parameters used in Model 1b.

Rock Parameters	Rock density kg/m^3	Porosity	Horizontal permeability, 10^{-15} m^2	Vertical permeability, 10^{-15} m^2
topk	2500	0.1	100.0	1.50
capk	2500	0.01	0.08	0.04
andd	2650	0.06	25.0	25.0
ande	2650	0.06	36.0	36.0
brcch	2500	0.09	12.50	12.50
brccm	2500	0.09	2.20	2.20
side1	2500	0.01	0.16	0.08
side2	2500	0.01	0.08	0.04
base1	2500	0.01	3.0	6.0
base2	2500	0.01	0.72	0.72

For all production and spring wells the DELG option (autough2, 2008) is used which allows a discharge proportional to the pressure above some cut-off pressure value. The spring wells have the form:

$$q_m = \mathrm{PI}\,\frac{k}{\nu_f}(p - p_{\mathrm{cut-off}}) \tag{2}$$

with

$$\frac{1}{\nu_f} = \frac{k_{rl}}{\nu_l} + \frac{k_{rv}}{\nu_v} \tag{3}$$

here q_m is the mass flux, *PI* is the productivity index, k is the absolute permeability, ν_f, ν_l and ν_v are the kinematic viscosities of the fluid, liquid and vapour, respectively, p is the reservoir pressure, $p_{cut\text{-}off}$ is the trigger pressure at which the well stops flowing, k_{rl} and k_{rg} are the relative permeabilities for the liquid and vapour phases, respectively.

2.1. Natural state

The aim of the first stage of the modelling is to set up a 2D natural state model which gives similar initial conditions (pressure, temperature and vapour saturation) to the 3D Darajat model.

Model 1a: A 2D model was set up based on a North West–South East vertical slice through the 3D Darajat model. The vertical grid structure, permeability distribution, heat inputs, deliverability of the spring blocks and boundary conditions from the 3D Darajat model are applied to this 2D model.

The permeability structure of the original 3D model was simplified to include fewer rock types. Grid structure and the rock type distribution of Model 1a are shown in Fig. 1. The rock types and their parameters are summarized in Table 1.

Three spring blocks are used at locations closest to the springs in the 3D model. Table 2 summarizes the rock properties, boundary conditions, deliverability conditions and relative permeability functions used in the steady state Model 1a.

Table 2
Parameters used in Model 1a.

Rock parameters	
Heat conductivity: 2.50 W/m^2 °C	Specific heat: 1000 J/kg °C
Basement boundary conditions of outer zone blocks	
Heat input: 0.06 W/m^2	
Basement boundary conditions of the reservoir blocks	
Pressure: 126.0 bar	Vapour saturation: 0.25
Deliverability of spring blocks	
Productivity index: 1.09E − 9 m^3	Cut-off pressure: 28 bar
Relative permeability-linear curves	
Slr: 0.75 Svr: 0.0 Spr: 0.25	