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Simulation of Heat Extraction for the Habanero 1 and 3 Doublet Using a Conditioned Discrete Fracture Network Model

Chaoshui Xu, Peter Dowd and Zhao Feng Tian

University of Adelaide, South Australia, Australia

peter.dowd@adelaide.edu.au

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ABSTRACT

The Habanero 1 and 3 doublet is the major component in the original electricity generation plan for the Geodynamics geothermal project in the Cooper Basin of South Australia. Various heat extraction studies have been conducted using simplified models such as a single fracture connecting the two wells or an equivalent porous medium representing the reservoir. In our approach, a more realistic fracture model is constructed conditional on the seismic events generated during the fracture stimulation process of the reservoir. The fluid flow and heat transfer are then solved using the equivalent pipe approach using a simplified heat exchange model. The results are compared with those from other studies. We demonstrate that the combination of a discrete fracture network and an equivalent pipe approach is an efficient and effective means of modelling industrial-scale fluid flow and heat transfer in geothermal systems such as the Habanero reservoir.

1. INTRODUCTION

Potential hot dry rock (HDR) geothermal systems occur in deep underground crystalline rock. The rock matrix (granite) is almost impermeable with typical micro- or even nano-darcy scale permeability in fresh granite (e.g., Bear and Cheng, 2010, Selvadurai et al. 2005). The only economically viable pathway for geothermal flow is through a fracture network. However natural fractures in HDR reservoirs are generally closed or sealed with very low hydraulic conductivity (micron scale hydraulic aperture). In general, hydraulic fracture stimulation is required within the reservoir to create an enhanced geothermal system (EGS) for industrial-scale exploitation. The fracture stimulation process causes planes of existing (naturally occurring) fractures to slip against each other due to the reduction in effective normal stress. Slipping causes misalignment of fracture surface profiles resulting in lateral dilation, which essentially causes the hydraulic aperture of the fracture to increase (Baisch et al. 2009). In addition, fracture stimulation causes existing fractures to propagate and it also creates new fractures. The outcome of the stimulation is a fractured rock mass that can be exploited to produce heat by using fluid injection and production wells intersecting the reservoir.

After the fracture stimulation, it is vitally important to understand the detailed structure of the EGS in terms of fractures and their connectivity in order to evaluate properly the geothermal fluid flow characteristics and the heat extraction performance of the reservoir. However, due to the scale of the difficulty of modelling the detailed reservoir structure, existing approaches to geothermal reservoir flow modelling either take a very simplistic view of the fracture network or use a grossly approximated equivalent porous media approach. Typical examples include a penny-shaped fracture to represent the whole reservoir (e.g., Zhang et al. 2009, Mohais et al. 2012), a geological model that consists of a single fracture plus a permeable zone around the fracture termed the cataclastic zone (Vörös and Weidler, 2006) and an equivalent porous media approach (Xing et al. 2009). Detailed fractures and the fracture network are obviously not preserved in these models and therefore these models can, at best, only provide an approximate system-scale assessment. More realistic performance assessment of an EGS requires a detailed fracture model to represent the fractured reservoir. As there is no direct measurement of the fracture network within the reservoir on any meaningful scale for engineering modelling, the fracture model can only be constructed via a stochastic approach informed by indirect measurements such as seismic events detected during the fracture stimulation process (see below). As a result, such a model includes significant uncertainties and the effects of these uncertainties must be assessed so as to understand fully the features of the reservoir. The work reported here provides such an assessment.

2. THE HABANERO RESERVOIR FRACTURE MODEL

The fundamental step in the assessment of flow in, and heat extraction from, an EGS is to establish the fracture network model. During fracture stimulation, fracture initiation, propagation and slipping generate micro-seismic events that can be monitored by an array of geophones and their spatial locations determined. We believe that the resulting seismic point cloud can be used to determine not only the geographical extent of the reservoir, but also the amount of fracturing and the fracture network in the reservoir (e.g., Xu et al. 2013, 2014, Bruel 2007). A number of approaches have been attempted over the past few years to fit a more realistic fracture model conditioned by the seismic point cloud. These include the Markov Chain Monte Carlo (MCMC) approach (Xu et al. 2012, 2013), the RANSAC approach (Fadakar Alghalandis et al., 2013), the clustering approach (Seifollahi et al., 2013, 2014) and the stochastic fracture propagation (SFP) modelling approach (Xu and Dowd, 2014). The SFP model attempts to follow the fracture propagation sequence observed during the reservoir stimulation process.

Geodynamics' Habanero field is a major hot dry rock geothermal project located in the Cooper Basin of South Australia. Of the five wells (Habanero 1-4 and Jolokia 1) drilled in the field, four (H1, H3, H4 and J1) have been successfully completed. A trial run of the 1 MW pilot electricity generation plant was conducted successfully for 160 days in 2013 using Habanero 1 as the injection well and Habanero 4 as the production well. The circulation achieved a flow rate of 19 $l.s^{-1}$ and 215^{o}C production well-head temperature (Geodynamics 2014).

In this paper, we use the flow circulation loop between Habanero 1 and 3 as a case study to demonstrate our approach. Habanero 1 was drilled to a depth of 4421 m in 2003 and Habanero 3 to a depth of 4200 m in 2007. The successful November 2013 fracture stimulation of the reservoir was used to determine the location of the Habanero 3 well approximately 600 m North-East of Habanero 1. The 23,232 seismic events detected during reservoir stimulation were used as conditioning data in the methods cited above to construct more realistic detailed fracture models of the reservoir. The MCMC model is used here to demonstrate the fluid flow and heat extraction analysis. The model, which has 613 fractures, is shown in Figure 1. A connectivity analysis of this fracture model identifies 27,293 number of possible flow pathways between H1 and H3. For detailed analysis of the fracture model, readers are referred to Xu et al. (2012, 2013) and Xu and Dowd (2014).

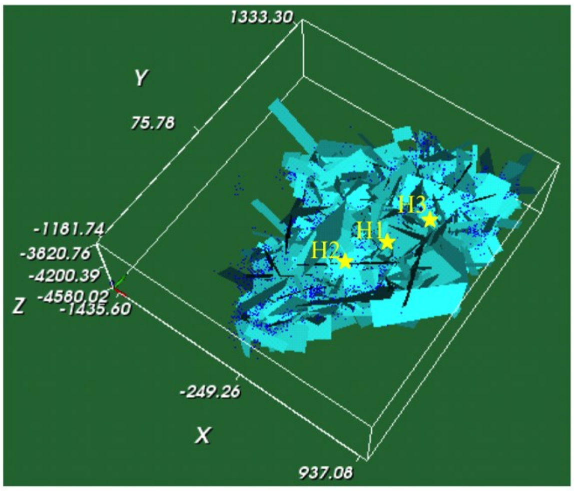

Figure 1: Fracture model of the Habanero reservoir (Xu et al. 2012)

3 FLOW MODELLING AND HEAT EXTRACTION ANALYSIS

Fluid flow through a rock mass can be modelled as an equivalent porous medium including the dual-permeability/dual-continuum method (e.g., Pruess 1990, Pruess and Narasimhan, 1985, Xing et al. 2009), as a discrete fracture network using the finite element method (e.g., Dershowitz et al., 2004), as a stochastic continuum or fractured continuum (e.g., Tsang et al. 1996, Oda, 1985, Lough et al. 1997, Lee et al. 2001) and as an equivalent pipe network (e.g., Dershowitz and Fidelibus 1999, Xu et al. 2014). These approaches all have their own advantages and limitations. In this work, we use the equivalent pipe network approach as it greatly simplifies the problem and significantly increases the computational efficiency. In this approach, the 3D fracture network model is transformed to a pipe network with equivalent hydraulic conductivity, i.e., fractures are represented as pipes originating and ending at centres of fracture intersection traces. Using the simplest geometrical approach, as illustrated in Fig. 2, the equivalent pipe conductance can be calculated approximately as

$$C = T \cdot \frac{W}{L} \tag{1}$$

where T is the transmissivity of the fracture and, using the parallel plate assumption:

$$T = \frac{g a^2}{12 \vartheta} \tag{2}$$

where a is the hydraulic aperture of the fracture and ϑ is the dynamic viscosity of the fluid (Jing and Stephansson, 2007). The pipe length L is the distance between the mid-points of the two intersection traces on the fracture and the pipe width is W=0.75*(L_1+L_2), following Dershowitz et al. (1999). The quantity of flow between these two fracture intersections can then be expressed as $Q = C{\cdot}\Delta h$, where Δh is the hydraulic head loss between the two intersections. Using these relationships and the fracture network connectivity information, a system of simultaneous equations can be set up to solve the hydraulic heads within the fracture network and hence the flow rates using the method detailed in Priest (1983) and Bodin et al. (2007). The main advantage of the equivalent pipe network approach is the simplification of the topology of the fracture network to improve the efficiency of flow modelling, particularly for large fracture networks.

For heat extraction, we use the simplified heat exchange model proposed in Xu et al. (2014) based on Newton's law of cooling. The heat exchange between the geothermal fluid and the rock matrix is evaluated from the fracture network and the contact areas between fractures and rocks. The fluid participating in the heat exchange is derived from the fluid flow model given above. The hydrothermal coupling then becomes (ignoring head conduction in the fluid) the heat flux balance between the thermal energy absorbed by the fluid:

$$q = \dot{m} c_f \Delta T_f \tag{3}$$

and the energy released by the rock matrix is:

$$q = \dot{m} h_c A \Delta T_f \tag{4}$$

where $\dot{m}$ is the fluid mass flow rate through the block, c_f is the specific heat of the fluid, ΔT_f is the temperature difference before and after the fluid passes through the block, h_c the heat transfer coefficient, A is the contact area (rock and fluid in our case) and q is treated as a heat sink. Note that q is a potential heat source (for the rock matrix) if the temperature of the passing fluid is higher than the rock block, which could happen depending on fractures and flow paths. The reservoir temperature model is then evaluated as a heat conduction system that can be solved by a finite difference scheme defined as follows:

$$\frac{T_{i+1}^{t}-2\cdot T_{i}^{t}+T_{i-1}^{t}}{(\Delta x)^2}+\frac{T_{j+1}^{t}-2\cdot T_{j}^{t}+T_{j-1}^{t}}{(\Delta y)^2}+\frac{T_{k+1}^{t}-2\cdot T_{k}^{t}+T_{k-1}^{t}}{(\Delta z)^2}=\frac{1}{\alpha}\cdot\frac{T_{ijk}^{t+1}-T_{ijk}^{t}}{\Delta t}-\frac{s}{k} \quad (5)$$

where s is the heat sink/source derived from the heat exchange discussed above plus the heat source generated by the in-situ rock radiogenic process and the heat gain/loss of the reservoir from/to the rocks surrounding the reservoir model. The basic heat conduction system is shown in Figure 3.

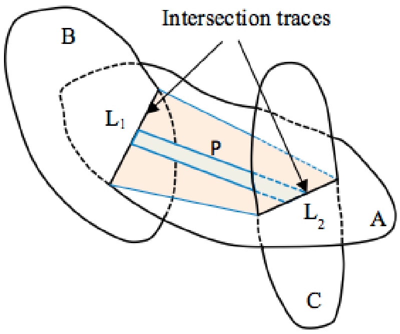

Figure 2 Equivalent pipe conductance calculation

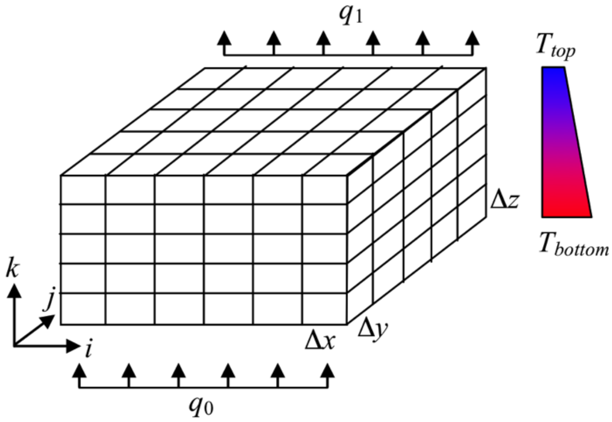

Figure 3: Heat conduction model of the reservoir

4 HEAT EXTRACTION SIMULATION FOR THE H1-H3 DOUBLET

The hydraulic aperture of fractures is the most critical parameter that determines the fluid flow through the reservoir. This variable is perhaps the least known and the most difficult to model in HDR applications. Although some assumptions are questionable, Baisch et al. (2009) attempted to use the magnitude of the stimulation-induced seismic events to estimate the cumulative shear slips within the Habanero reservoir, which can then be used to assess changes in fracture apertures. Due to the significant depth of HDR resources, any direct measurement of fracture apertures in a reservoir is impossible and thus aperture values have to be assumed for flow modelling. As a consequence there are significant uncertainties involved and it is important to assess the effect of these uncertainties on the performance of the reservoir.

In the work reported here, to demonstrate the incorporation of the aperture uncertainty into the fluid flow and heat extraction analysis, we assume a normal distribution of fracture apertures within the reservoir. The two distributions examined in this research are shown in Table 1. The mean value of 240 µm is from the analysis reported in Xu et al. (2014) and is chosen so as to achieve an average reservoir production rate of approximately 35 $l.s^{-1}$.

Table 1 Normal distribution parameters used for the uncertainty assessment

	Mean (µm)	Standard deviation (µm)	Coefficient of variation
Case 1	240	50	0.208
Case 2	240	100	0.417

During the simulation, the aperture of each fracture within the fracture network is generated randomly from its specified distribution. Any possible correlation between fracture aperture and fracture size (Baghbanan and Jing, 2007, Priest, 1993b) is not incorporated in our model at this stage. The equivalent pipe conductance for the pipe network model is then calculated followed by fluid flow and heat extraction simulations. The key hydro- and thermo-properties used in the simulation are summarized in Table 2. The hydraulic head difference at the bottom of the well between the injection well (H1) and the production well (H3) is kept constant at 15 MPa based on Vörös and Rothert (2009) and the injection temperature is set at 95°C (Vörös and Rothert, 2009, Geodynamics, 2014). The initial temperature boundary condition is set at 260°C at the depth of 4600m and the initial temperature gradient is 50°C.km^{-1} (Wyborn, 2012).

Table 2 Hydro and thermal properties used

Property	Value	Reference	Symbol
Kinematic viscosity of fluid	10^{-6} m^2.s^{-1}	Ref 1	ν
Average heat transfer coefficient	1500 W.(m^2.K)$^{-1}$	Ref 2	h_c
Fluid specific heat	4200 J.(kg.K)$^{-1}$	Ref 2, 3	c_f
Rock specific heat	920 J.(kg.K)$^{-1}$	Ref 2, 3	c_m
Fluid density	1000 kg.m^{-3}	Ref 2, 3	ρ_f
Rock density	2700 kg.m^{-3}	Ref 2, 3	ρ_m
Rock thermal conductivity	3 W.(mK)$^{-1}$	Ref 2, 3	λ_m
Average radiogenic heat generation rate (rock)	1.85×10^{-9} W.kg^{-1}	Ref 2, 3	$\dot{q}_g$

Ref 1: Priest (1993); Ref 2: Bundschuh and Suárec-Arriage (2010); Ref 3: Wyborn (2012)

Table 3 Summary statistics of the simulations

		Mean	St. Dev.	Coeff. Var.	Minimum	Maximum
Flow (l.s^{-1})	Case 1	34.46	5.73	0.166	22.78	54.0
	Case 2	38.54	12.39	0.321	13.78	70.67
Production temperature (K)	Case 1	508.20	0.85	0.00167	506.5	510.8
	Case 2	508.30	1.30	0.00256	505.6	512.6
Power Extracted (MW)	Case 1	20.27	3.37	0.166	13.51	31.87
	Case 2	22.69	7.32	0.323	8.24	42.02

A total of 150 independent simulations of one month of heat extraction were conducted for each case. The summary statistics of the simulations are listed in Table 3. Their respective distributions are shown in Figures 4, 5 and 6. The following observations can be made:

- As expect, the output is very sensitive to changes in fracture apertures. For the two cases examined, significant variations in terms of reservoir outputs are observed.
- All distributions are approximately normal but they all tend to be positively skewed. This is because the flow and other outputs are directly related to the aperture by the cubic law and therefore they will be positively skewed even when the aperture follows a normal distribution.
- All ratios of the coefficient of variation between the two cases are approximately 2, which conforms to the input.
- The variability in production temperature is extremely low. This is because only one month of production is simulated. For the Habanero reservoir, simulations show that the production temperature does not change significantly over the first five years at a production rate of 35 l.s^{-1} (Xu et al. 2014). At this production rate, the total reduction in the production temperature after 20 years of production is 35°C.
- The distribution of power generated follows closely that of flow rate. This is because as there is little variability in temperature, the variability in power is primarily a function of the flow rate.

Figure 7 shows a typical reservoir temperature distribution during heat production.

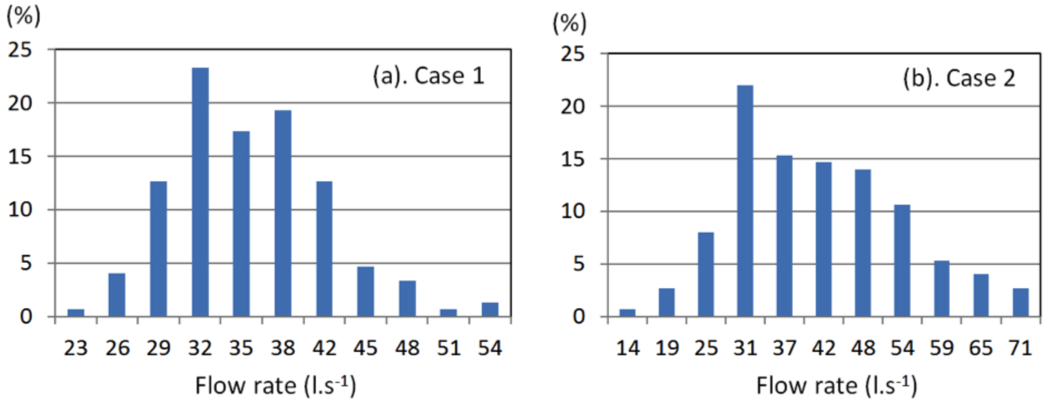

Figure 4 Flow rate distributions

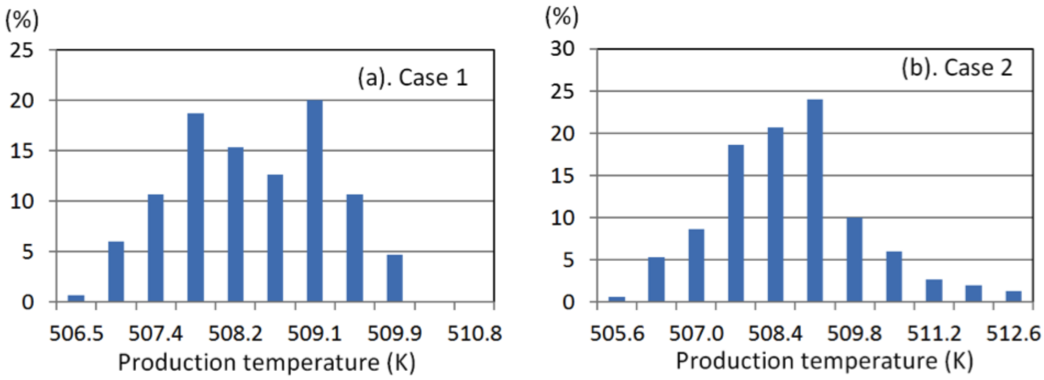

Figure 5: Temperature distributions after one month of production

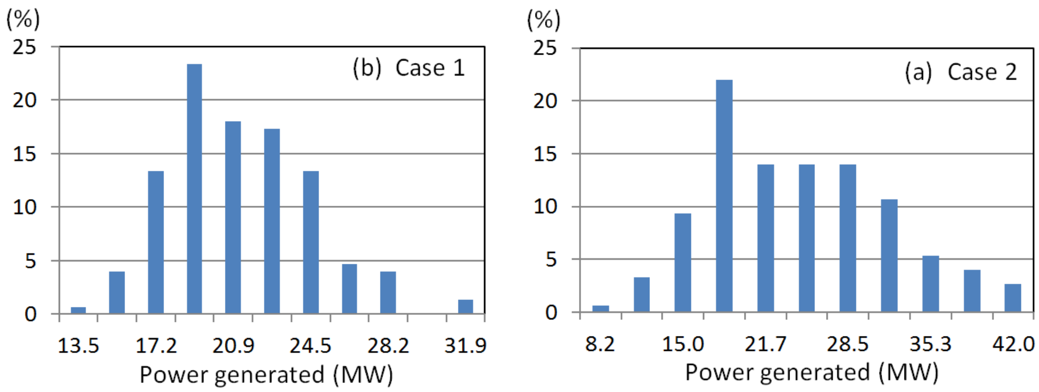

Figure 6: Distributions of power produced after one month of production

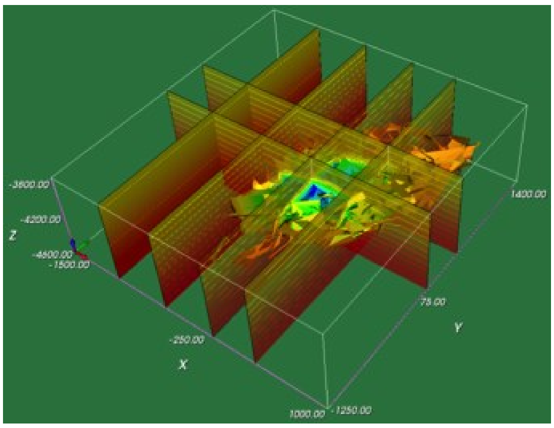

Figure 7 Example of the temperature distribution within the reservoir

5 CONCLUSIONS

This paper describes a fluid flow and heat extraction statistical model for assessing the effect of the most critical uncertainties – fracture apertures on the performance of the Habanero reservoir. The fracture model of the reservoir is conditioned on the seismic events detected during the fracture stimulation process. The flow model is solved using the equivalent pipe network method and the heat extraction is solved using a simplified heat transfer model. The fracture apertures within the reservoir are assumed to follow a normal distribution and two cases of the distribution (same mean but different standard deviations) are simulated in this study to assess their impact on the reservoir performance. It was found that the reservoir outputs in terms of production rate and production power are very sensitive to the variation in fracture aperture. Their ranges of variations are significant which demonstrate the importance of assessing the uncertainty involved with the aperture assumption. Their distributions are positively skewed although they are still reasonable approximations of normality. The variation in production temperature in this case is small due to the short span of production time simulated.

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