# FINITE ELEMENT MODELLING FOR PRODUCTIVITY OF GEOTHERMAL RESERVOIRS VIA EXTRACTION WELL

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## ABSTRACT

The major process in geothermal energy stimulation is the injection and extraction of fluid through wells to generate power. One of the methods utilised in examining the long-term behaviour of such systems is modelling. In this paper, a three-dimensional (3-D) thermo-hydro-mechanical (THM) coupled model of a geothermal reservoir is developed to probe the productivity of the reservoir via the extraction well at different placement locations using a Multiphysics Finite Element (FE) application solver. Coupling between the thermo-hydro (HT) processes was achieved through convective velocity term and thermo-mechanical (MT) coupling through temperature and thermal expansion coefficient. Therefore, the parameters analysed were the total net energy rate, enthalpy and temperature using a boundary probe function and a parametric study step solver. The results showed that when the extraction well was placed nearer to the injection well, the productivity was found to be lower after only a few years of production, on the other hand, further placement of wells gives higher productivity.

***Keywords:*** *Geothermal reservoir; thermo-hydro-mechanical (THM) coupling; FE modelling; productivity.*

## 1. Introduction

Geothermal energy is a renewable source and as such listed with solar, wind and biomass asalternative energy options[1,2]. To simulate and evaluate the behaviour of a deep geothermal system for commercial viability, one needs a reliable code that can handle the complexity of subsurface flow [3]. In this work, a geothermal reservoir model was developed using a multiphysics finite element (FE) solver (COMSOL) with a link to MATLAB to investigate the productivity of a geothermal reservoir via the extraction well under the effect of a coupled Thermo-Hydro-Mechanical (THM) processes.

## 2. FE Modelling of Coupled THM Processes

In this work, only a brief description of the formulations of coupled THM processes will be addressed. Detailed mathematical and finite element formulationshavebeen fully discussedin [4].In a fractured porous medium, the governing equations described for fluid flow are the conservation of mass and Darcy's law. For the matrix, the equations areexpressed as,

$$S\frac{\partial P}{\partial t}-\beta\frac{\partial T}{\partial t}+\nabla\cdot q=Q_h,\ q=\frac{k}{\mu}(-\nabla_P+\rho_w g) \tag{1}$$

where$S$is the specific storage, $P$is the pressure, $T$is the temperature, $\beta$ is the fluid compressibility, $\nabla$is the vector differential operator,$q$is the Darcy's volumetric flux, and $Q_h$is the source term for the matrix.Also, $k$ is the permeability, $\mu$is the dynamic viscosity, $\rho_w$is the density of water, and $g$is the acceleration due to gravity. For the discrete fractures, the equationsare given as,

$$d_f S\frac{\partial P}{\partial t}-\alpha\frac{\partial d_f}{\partial t}+\nabla\cdot(b_h.q_h)-\beta\frac{\partial T}{\partial t}=Q_h,\ q_f=\frac{b_h^2}{\mu}\mathrm{I}(-\nabla_{pf}+\rho_w g) \tag{2}$$

where $d_f$ is the mechanical aperture, $\alpha$ is the biot's coefficient, $b_h$ is the hydraulic aperture and I is the identity matrix.The equations definedfor heat transport are the conservation of energy and Fourier's law. For the matrix, the equations areexpressed as,

$$C_P \rho \frac{\partial T}{\partial t} + \nabla \cdot q_T = Q_T \, , q_T = -\lambda \nabla T + C_P \rho T \tag{3}$$

where $C_p$ is the specific heat capacity of the matrix, ρ is the density of the matrix, λ is the thermal conductivity, $q_T$ is the heat flux, $C_{pw}$ and $Q_T$ is the heat source. The equations describing the discrete fractures aregiven as,

$$d_f C_{Pw} \rho_w \frac{\partial T}{\partial t} + \nabla . q_T = 0 \, , \; q_T = -\partial_f \lambda \nabla T + b_h \, C_P \rho q T \tag{4}$$

The governing equation defined for mechanical behaviour are the conservation of momentum and the Biot's poroelastic model, which are expressed as,

$$\nabla \cdot (\sigma' - \alpha P \mathrm{I}) + \rho g = 0 \, , \; d\sigma' = D\left(d\varepsilon - \alpha_T \Delta T \mathrm{I}\right) \tag{5}$$

in which $\sigma'$ is the effective stress, $\alpha_T$ is the thermal expansion coefficient, $\Delta T$ is the temperature increment, $\varepsilon$ is the total strain and $D$ is a forth-order material tensor. For nonlinear and isotropic elasticity, the material tensor is given as,

$$D = \lambda \delta_{ij} \delta_{kl} + 2G \delta_{ik} \delta_{jl} \, , \varepsilon = \frac{1}{2}\left(\nabla u + (\nabla u)^T\right) = \nabla^S u \tag{6}$$

where $\delta$ is the Kronecker delta, $G$ is the shear modulus, $u$ is the displacement vector and the superscript T means the transpose of the matrix.

Furthermore, the green theorem and the method of weighted residuals (MWR) are applied to the governing equations provided above to derive the weak formulation of the problem as

$$\int_\Omega w \rho S \frac{\partial P}{\partial t} d\Omega - \int_\Omega \rho \nabla w^T \cdot q d\Omega + \int_\Gamma w \rho (q \cdot n) d\Gamma - \int_\Omega w Q_h d\Omega = 0 \tag{7}$$

$$\int_\Omega w \rho C_P \frac{\partial T}{\partial t} d\Omega + \int_\Omega w \rho C_p q_T \cdot \nabla T d\Omega - \int_\Gamma \nabla w^T \cdot (-\lambda \nabla T) d\Omega + \int_\Gamma w(-\lambda \nabla T \cdot n) d\Gamma - \int_\Omega w^T Q_T d\Omega = 0 \tag{8}$$

$$\int_\Omega \nabla \cdot w\left(\sigma' - \alpha P \mathrm{I}\right) d\Omega - \int_\Omega w \rho g d\Omega = 0 \tag{9}$$

where $w$ is the weighting function, Ω represents the model domain and г denotes the boundary domain. The boundary conditions are specified for all field functions P, T and U. The weak forms of the THM balance equations were spatially discretised using the Galerkin method. Primary variables are pressure P, temperature T, and displacement U and can be approximated by interpolation functions as,

$$P^y = N_P P \tag{10}$$

$$T^y = N_T T \tag{11}$$

$$U^y = N_U U \tag{12}$$

where P and T are the scalars of the nodal values of the unknowns and U is nodal vector. $N_P$, $N_T$ and $N_U$ are the shape functions for P, T and U respectively. The finite element formulation of the governing equations can be given in a matrix form as

$$M_h^m P'^m + K_h^m P^m - q_h^m = 0 \tag{13}$$

$$M_T^m T^{'m} + K_T^m T^m - q_T^m = 0 \tag{14}$$

$$\int_\Omega B^T \sigma^{'} d\Omega - C^m P^m - f_M = 0 \tag{15}$$

where M, K and C are process-specific mass, Laplace and coupling matrices. The term *f* contained the contributions of the coupled processes and B is the strain-displacement matrix.

**3. Problem Description**

Based on the formulations presented in the previous section, a 3-D FE model of the Urach Spa geothermal reservoir was developed. The model was 800 m long, 300 m wide, with estimated high of 300 m[5]. However, due to symmetry only half of the reservoir was modelledwith two discrete fractures of 2mm thickness each. The initial temperature of the reservoir was given as $T_0$ =10°C + 0.03[K/m]*z, where 10°C is the surface temperature, 0.03 [K/m] is the geothermal gradient, and z is the reservoir depth in metres. Also, the initial pressure of the reservoir was hydrostatic and initial stresses applied were lithostatic in all directions, and other reservoir parameters utilisedwere available from literature [5]. Moreover, the boundary conditions (BC) used in the model wereDirichlet for both the hydraulic and thermal processes;for the mechanical process, all the reservoir boundarieswere assumed to be roller except the body load applied at the top.

**4. Results and Discussions**

A comprehensive study was carried out on injection-extraction well separation distance. The positions of the extraction well were varied systematically using a parametric sweep function to examine the location that could yield maximum energy in the reservoir. The parameters investigated were temperature, enthalpy, and the total net energy rate under a long-term simulation of 30 years. The first sets of results presented were the effect of cold water distribution in the matrix and the fractures. The injected fluid mainly flows in the direction of fractures due to their higher permeability and connected the production well effectively. However, the cold water injection decreases the temperature of the rock after nearly seven years of the simulation. Also, the cooling fronts presented showed that the reservoir temperature is 5°C below the initial rock temperature after one year of injection as shown in Figure 1(A), 7°C after five years and 8°C after ten years as presented in Figures 1(B) and 1(C), respectively.

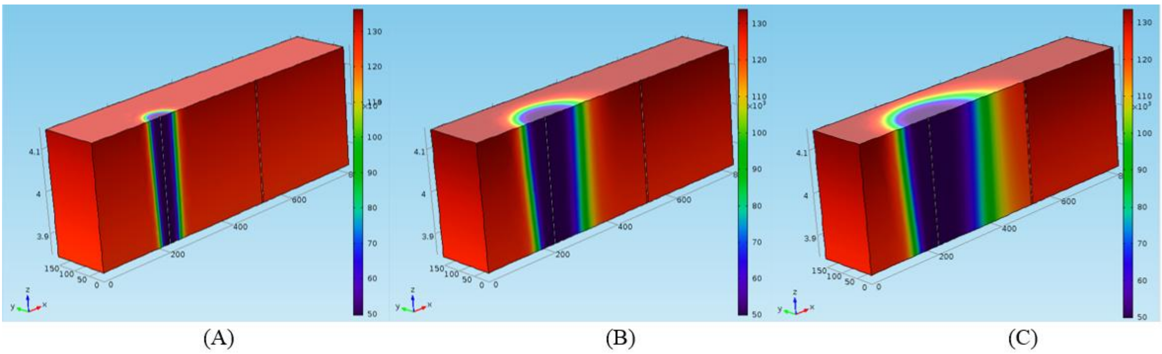

Figure 1: (A) Cold water distribution after one year of production (ºC), (B) Cold water distribution after five year of production (ºC), (C) Cold water distribution after ten year of production (ºC).

The second sets of results analysed in this work include the temperature, enthalpy and the total net energy rate. The temperature changes at the seven positions of the production wells presented in Figure 2(A) showed a temperature drawdown after six years at the production well that was the closest to the injection (300 m) and ten years at the well that was the second closest (350 m). At twelve and half year drawdown was observed at the well third closest to the injection (400 m) and 17 years at the well that was furthest (450 m). From the furthest position onwards there was no significant drawdown observed because the cold water effect is longer reaching the wells after 30 years of simulation. The enthalpy results presented in Figure 2(B) also showed similar behaviour to that of the temperature due to the close relationship between the two parameters in systems thermodynamics. In the case of the total net energy rate produced at the well head of the reservoir, a significant drop is observed from 5.5 MW to 2.5 MW approximately within the first year of production, because the injected pressure starts to reactivate the existing fractures and also forming new hydraulic fractures (i.e. the breakthrough pressure). The net energy later stabilises after in almost all the cases except for the wells closer to the injection well as shown in Figure 2(C).

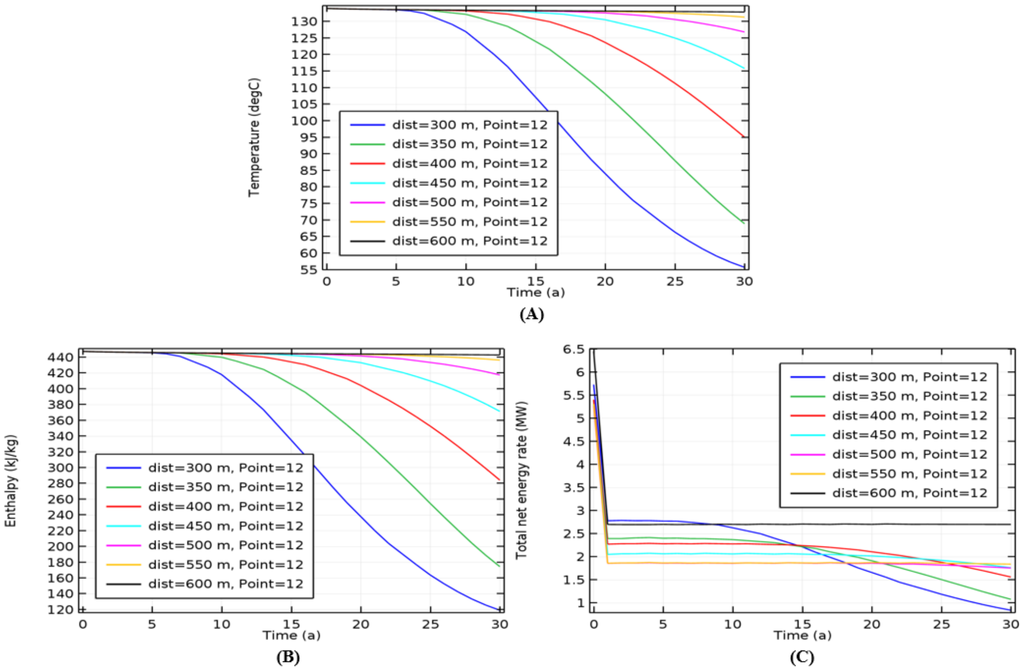


Figure 2: (A) Production temperature, (B)Enthalpy and (C) Total net energy rate

## 5. Conclusion

A three-dimensional numerical model of a coupled thermo-hydro-mechanical interaction in a naturally fractured reservoir has been developed using the finite element method. The developed model serves as a mechanism for evaluating HDR geothermal reservoir operations and for assessing its long-term performance and energy extraction potential using a parametric sweep solver. The studies reported here have focused attention on the significance of well (i.e. production) placement in HDR geothermal reservoir operations. The model has the potential to serve as a tool for assessing the behaviour of deep subsurface media in the context of other related technologies such as hydrocarbon reservoirs, carbon dioxide ($CO_2$) sequestration reservoirs and waste disposal reservoirs.

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