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Numerical investigation of temperature distribution in a confined heterogeneous geothermal reservoir due to injection-production

Sayantan Ganguly[a], Lippong Tan[a,*], Abhijit Date[a], Mandalagiri Kumar[b]

[a]*School of Engineering, RMIT University, Melbourne 3000, Australia*
[b]*Civil Engineering Department and Indo-French Cell for Water Sciences, Indian Institute of Science, Bangalore 560012, India*

Abstract

The present study deals with the modeling of transient temperature distribution in a heterogeneous geothermal reservoir in response to the injection-production process. The heterogeneous geothermal aquifer considered here is a confined aquifer with homogeneous layers of finite length and overlain and underlain by impermeable rock media. The heat transport modes considered are advection, conduction in the geothermal reservoir and heat transfer to the confining rock media. Results show that heterogeneity plays a very significant role in determining the transient temperature distribution and controlling the advancement of the thermal front in the reservoir. A one-dimensional (1D) analytical model for temperature distribution in the geothermal reservoir is also derived in this study. Results from a simpler version of the numerical model are compared with the results from the analytical solution which are in good agreement with each other.

Keywords: Geothermal reservoir; Heat transport in porous media; Thermal front; Heterogeneity; Numerical modeling; Analytical solution.

1. Introduction

Geothermal reservoir operation is essentially an injection-production process where geothermal steam/hot water is extracted for power production. A fraction or the whole waste-water which is produced after heat extraction is then reinjected back into the geothermal reservoir. The purposes of reinjection are safe disposal of the thermal water [1], maintaining the reservoir pressure which gradually declines due to continuous production of geothermal fluid [2] and enhancing the heat extraction efficiency of a reservoir [3]. In spite of these benefits, there lies the possibility of cooling of the production wells due to premature breakthrough of the cold-water thermal front generated by the reinjection

* Corresponding author. Tel.: +61 3 9925 7614; fax: +61 3 9925 6108.
E-mail address: lippong.tan@rmit.edu.au

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since the reinjected fluid is much colder than the geothermal reservoir environment [4,5]. Thermal-breakthrough affects the reservoir efficiency to produce power severely. Hence to maintain the reservoir efficiency and for longer life of the reservoir, the injection-production well scheme is to be properly designed and injection and production rates are to be fixed properly. Modelling the transient temperature distribution due to injection-production is thus very important. Heterogeneity of the geothermal aquifer is also an important factor to consider in the heat transport phenomenon in porous media since a homogeneous medium is practically very rare in nature. In the geothermal literature the heterogeneity of the aquifer is not well addressed. [6] derives an analytical solution for temperature distribution in a geothermal reservoir with continuous heterogeneity. Geothermal reservoirs are found which are comprised of a series of homogeneous finite layers. [7] cited literatures based on layered porous media observed in natural environments such as stratified soils [8], aquifers and aquitards [9] or in constructed environments such as estuary sediment caps [10]. One such confined and layered geothermal reservoir is considered in this study. The objective of the present study is to develop a numerical model to predict the transient temperature distribution in a heterogeneous geothermal reservoir system due to injection-production. The numerical modelling is performed using the software code DuMu^x [11]. The heat transfer processes taken into account are the advection, conduction and heat transport to the confining rocks. The aquifer considered here is a confined one and consists of vertical layers with different thermo-geological properties. A simpler version of the numerical model for a 1D heterogeneous geothermal aquifer is compared with an analytical model derived here. The comparison of temperature distributions derived using both the models shows very good match to each other.

2. Mathematical and numerical modeling

The present study is about developing a coupled thermo-hydrogeological model for temperature distribution in a heterogeneous geothermal reservoir due to thermal injection. The three-dimensional (3D) fluid flow equation in porous media is given by

$$S\frac{\partial h}{\partial t} - \nabla \cdot \{K \cdot \nabla h\} = q_f \tag{1}$$

where h: hydraulic head, K: hydraulic conductivity of the aquifer; S: specific storage and q_f : source term.

The confined aquifer considered here consists of two homogeneous layers (although the model can be extended for n number of such layers), overlain and underlain by impermeable rocks. The whole aquifer system with injection-production wells is presented schematically in Fig. 1. 3D heat transport equation for single phase fluid flow in porous media for two layers of the aquifer is

$$\frac{\partial}{\partial t}\left\{\left(1-\phi_{1,2}\right)\cdot \rho_{1,2}\cdot c_{1,2}\cdot T_{1,2}(x,y,z,t)+\phi_{1,2}\cdot \rho_w \cdot c_w \cdot T_{1,2}(x,y,z,t)\right\}+\nabla\cdot\left\{u_w\cdot\rho_w\cdot c_w\cdot T_{1,2}(x,y,z,t)\right\}+q_1-q_2=\nabla\cdot\left\{\left(\lambda_{1,2}\cdot\nabla\right)\cdot T_{1,2}(x,y,z,t)\right\} \tag{2}$$

where the subscripts 1,2 stand for the two layers of the geothermal aquifer (Fig. 1), T: temperature; c_r and c_w: specific heats of rock and water; ϕ:porosity of the aquifer; ρ_r and ρ_w: densities of the rock and water; u_w : velocity of groundwater; λ_x and λ_y : thermal conductivities of the geothermal aquifer in longitudinal and vertical directions; t : injection time; x and y : distances in longitudinal and vertical directions and q_1 and q_2 are the heat transfer fluxes to the overlying and underlying rocks. The above heat transport equation (2) coupled with the groundwater flow equation (1), is solved in the model to derive the transient temperature distribution in the model domain.

The model domain considered here is a confined porous aquifer of dimensions ($L\times B$) 600 m×30 m, consisting of two vertical layers of length 260 m (L_1) and 340 m (L_2). The aquifer is underlain and overlain by rock media of thickness 90 m (b_1) and 80 m (b_2), respectively. Initial temperature of the aquifer is 80°C (353K). Cold water at a temperature of 20°C (293 K) is injected at a rate of 300 m^3/day by an injection well at a distance 200 m away from the left end of the aquifer. Hot-water is extracted by a production well at a distance 200 m from the injection well. At the right boundary of the domain a pressure of 30.0 MPa and a temperature of 80^{0}C are considered as boundary conditions whereas a pressure of 31.2 MPa and the same temperature of 80^{0}C are considered to be the boundary conditions for the left boundary. Hence there is an existing regional groundwater flow driven by the gradient from left to right existing prior to the injection. The overlying and underlying rock media are of low permeability and heat loss occurs from the aquifer by only by heat conduction due to the temperature gradient between the aquifer and the rock media. All the physical and thermal properties used in the modeling study are listed in Table 1.